SITE-SPECIFIC CRITICAL LOADS OF ACID DEPOSITION ON SOILS IN THE PROVOST-ESTHER AREA, ALBERTA

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FOREWORD

In 1999 Alberta Environment implemented the Acid Deposition Management Framework([1]) for long-term management of acid deposition. In the development of the framework, it was discovered that a specific study of soil and water sensitivity in an area in southeastern Alberta (the Provost-Esther area) is required due to the apparent sensitivity of the area, and the predicted level of acid deposition in the area. Ensuring that a study is completed is a responsibility of Alberta Environment. This report was commissioned by the Air Research Users Group of Alberta Environment, and presents the data and conclusions arising from this study of soil and water sensitivity in the Provost-Esther area of southeastern Alberta.

Determining soil and water sensitivity to acid deposition is an area of current scientific interest. There are several methods that can be used to determine sensitivity, none of which are applicable under all conditions and in all regions. In order to determine the critical loads in southeastern Alberta, a necessary first step is to review the methods and models utilized elsewhere in establishing critical loads. The second step is to apply those methods and models judged applicable to the area, and derive a critical load for the area.

Critical loads are the foundation of the Acid Deposition Management Framework. The results of this study both establish a method for derivation of critical loads in Alberta, and apply those methods to the derivation of critical loads for an area in southeastern Alberta. The material in this report will be used in the next full assessment of acid deposition in Alberta, scheduled for 2004.

Readers interested in learning how this study fits into the provincial framework are referred to the document in which the framework is described. The document *Application of Critical, Target and Monitoring Loads for the Evaluation and Management of Acid Deposition* can be obtained from the Alberta Environment Information Centre (780/422-2079 or 403/297-3362) or on the Internet at http://www3.gov.ab.ca/env/info/infocentre/publist.cfm.

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1 The Acid Deposition Management Framework is described in: Clean Air Strategic Alliance and Alberta Environment (1999) *Application of Critical, Target, and Monitoring Loads for the Evaluation and Management of Acid Deposition.* Edmonton, AB. 78 pp.

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SUMMARY

In this study, the available methods to derive critical loads are reviewed, and those judged applicable to derivation of site-specific critical loads, are applied to an area in east-central Alberta between 110° and 110.5° W longitude, and 51.5° and 52.5° N latitude (the Provost-Esther grid cell or study area). The two specific objectives of this study are:

1) *Development of Methodology:* To map the soil types, land uses and aquatic systems within the study area, to analyze samples collected from the various soil types and/or water bodies present within the area, and to estimate the site-specific critical load for each sample using one or more mathematical receptor models.
2) *Estimation of Critical Load:* Using the derived methods, to provide an estimate of the critical load for the Provost-Esther grid cell.

Development of the methodology involved a review of critical load criteria, with emphasis on pH, base saturation, and the ratio of base cation (BC) to aluminum (Al) concentrations in the soil solution (for soils), and on acid neutralizing capacity (for water). Available data on soil types, land uses and water systems were then compiled, and a map displaying this information was generated. Based upon these data, a field sampling program was developed and implemented. The sampling program focused on potentially sensitive soils under native or range vegetation, avoiding areas under cultivation as agricultural practices such as fertilization may result in greater acid inputs to soil than from atmospheric deposition. Water samples were collected from one water body only, as lakes and sloughs in the study area were predominantly saline (not sensitive to acid deposition).

Estimation of critical loads for soils in the Provost-Esther study area started with a review of soil receptor models developed elsewhere for similar purposes. Data arising from the soil sampling program were then used as input into those models judged applicable for use in Alberta. Analysis of the one water sample collected confirmed that water bodies in the region were saline, and therefore, not sensitive to acid deposition. No further investigation of water systems was undertaken. The methods described in this report were developed during the study, and are recommended for application whenever and wherever in Alberta a study of critical loads is required.

As a result of the review and application of soil response models, it is recommended that the ARC model be used for future determination of critical loads in Alberta. The ARC model was originally developed for application in Alberta (it is based on semi-empirical relationships obtained from Alberta soils). The utility of this model is demonstrated in this report through comparison with the results of other models and methods for critical load derivation.

The second objective of this study was to examine, and if appropriate revise, the sensitivity assignment of the Provost-Esther grid cell. It is concluded that the coarse textured, potentially acid sensitive soils in the study area fall into a Moderate sensitivity category with respect to acidification. A Moderately sensitive category is defined in this study as having a critical load range of 0.2 to 0.5 keq H^+ ha^{-1} yr^{-1} ([2]) over a 100-year time period, or 0.5 to 1 keq H^+ ha^{-1} yr^{-1} over a 50-year time period.

2 The non-SI unit 'keq' (kiloequivalent), used throughout this report, is the same as the SI unit '$kmol_c$'.

Most of the sampled soils fell into this category, although some sites with higher and lower critical loads occurred as well. It was considered that most soils within any map unit (Land System) would be best represented by either the modal or 25th percentile critical load value, while recognizing that small areas with relatively low critical loads would also occur.

No sensitive soils were found to occur in the Provost-Esther grid cell. Moderate sensitivity soils occupy 11% of the area, and soils of low sensitivity the remainder. Applying the criteria specified in the assignment of sensitivity categories to grid cells in Alberta (Acid Deposition Management Framework), the Provost-Esther grid cell would be appropriately categorized as being of Moderate sensitivity.

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1.0 INTRODUCTION

In December 1999, Alberta Environment implemented the Acid Deposition Management Framework for the long-term, provincial management of acid deposition (Clean Air Strategic Alliance and Alberta Environment 1999). This framework is based upon the current understanding of the levels of acid deposition and the sensitivity of soil and water receptors in the province. Development of this framework included significant stakeholder consultation through Alberta's Clean Air Strategic Alliance.

Critical loads are the foundation of the framework. A critical load is a property of the receptor (soil, water), and is defined as the amount of acid input that can be received by the receptor that will not cause chemical changes leading to long-term harmful change to the receptor.

The province of Alberta is divided into grid cells measuring 1° latitude x 1° longitude, and each grid cell is categorized as being Sensitive, Moderately sensitive or of Low sensitivity to acid deposition based upon soil and water sensitivity databases. A Sensitive cell is defined as a cell within which 5% or more of the area is categorized as being Sensitive, and to such cells, a critical load of 0.25 keq H^+ ha^{-1} yr^{-1} is applied. A Moderately sensitive cell is defined as a cell within which less than 5% of the area is categorized as Sensitive, but where the total of Sensitive and Moderately sensitive areas equals or exceeds 5% of the cell area. To these Moderately sensitive cells, a critical load of 0.50 keq H^+ ha^{-1} yr^{-1} applied. The remainder of the grid cells are classified as being of Low sensitivity to acid deposition and are assigned a critical load of 1.00 keq H^+ ha^{-1} yr^{-1}.

In addition to critical loads, grid cells have also been assigned target and monitoring loads. Target loads are based upon the critical loads, with the added proviso that target loads be an expression of society's values – in the Alberta framework, target loads are set at 90% of the critical loads (0.22, 0.45 and 0.90 keq H^+ ha^{-1} yr^{-1} for the three sensitivity classes). These target loads are also the environmental objectives as defined in provincial environmental legislation. By establishing target loads below the critical loads, provincial stakeholders and Alberta Environment have established a system of preventing an increase in deposition to the level believed harmful (the critical load). An exceedance of a target load will initiate processes to reduce emissions such that deposition in the exceedance cell is reduced to or below the target load for that cell.

Monitoring loads are also assigned to the sensitivity classes; these are set at 70% of the critical loads. Exceedance of this load initiates studies of receptor sensitivity and monitoring of deposition – the results of such studies are used to revise the initial assignments of cell sensitivity (and therefore the assigned numerical loads). If the studies confirm model prediction and sensitivity, the cell is watched more closely to ensure that deposition does not increase to the point of a target load exceedance.

The Regional Lagrangian Acid Deposition (RELAD) model has been used to estimate the amount of acid deposition in Alberta. There are no grid cells currently receiving acid deposition in excess of their assigned critical or target loads. However, one cell spanning the southern part of Alberta-Saskatchewan border is predicted to be receiving more deposition (0.18 keq H^+ ha^{-1} yr^{-1}) than its assigned monitoring load (0.17 keq H^+ ha^{-1} yr^{-1}). As stipulated in the Alberta Acid Deposition Management Framework, Alberta Environment is responsible for conducting an evaluation of the monitoring data from this region, as well as conducting an evaluation of receptor sensitivity. The present study addresses the latter of these two requirements, an examination of the receptors in the cell, described herein as the Provost-Esther grid cell or study area.

The specific objectives of this detailed receptor sensitivity study are to develop the methods needed to conduct this evaluation (standard methods are not yet available), and using the derived methods, provide an estimate of the critical load for the soil types and water bodies present in the Provost-Esther study area. On the basis of these critical loads estimates, a recommendation regarding the sensitivity of the cell as a whole (the portion within Alberta) will be provided if appropriate.

1.1 The Provost-Esther Grid Cell (Study Area)

The grid cell to be investigated in this project is in eastern Alberta/western Saskatchewan. One half of the cell is situated in each province. The Alberta half is the subject of this study, the boundaries of which are:

- The Alberta-Saskatchewan border (110°W longitude) on the east
- 51.5°N latitude on the south
- 110.5°W longitude on the west, and
- 52.5°N latitude on the north.

This grid cell is herein referred to as the Provost-Esther grid cell or study area, after two towns located near the north and south extremities of the cell. The area of the grid cell is approximately 3,000 square kilometres.

1.2 Approach to Critical Load Determination

In order to validate or adjust the critical load currently applied to the study area (0.25 keq H^+ ha^{-1} yr^{-1}), it is necessary to determine the soil types and land uses within the cell, to analyze samples collected from the various soil types and water bodies present within the area defined above, and to estimate the site-specific critical load for each sample using one or more mathematical receptor models.

Critical loads are essentially a measure of the buffering capacity of the system. The buffering capacity can be altered by processes other than deposition of acidic substances from the atmosphere. Agricultural and range management practices may have a large impact on soil chemistry, and

therefore, make it difficult to assess the relatively small impacts of acid deposition on soils used for agriculture (crop production) or for livestock grazing. For this reason, the emphasis of this project was on soil and water systems that are not, or are minimally, affected by intensive farming and/or range management practices.

The terms of reference established for this study specified a number of tasks:

1. Compile available data on soil types, land uses and aquatic systems within the defined area, and generate a map showing this information.
2. Develop a sampling protocol to collect sufficient samples of soil and water to determine the critical load for each soil type/land use/aquatic unit.
3. Evaluate the available receptor models that are used to estimate critical loads. Obtain the information necessary to use those models judged to be applicable in Alberta.
4. Develop an analytical protocol to be used for the analysis of soil and/or water samples, ensuring that all of the data required to run each of the selected models is obtained from each sample.
5. Implement the field sampling protocol, and collect the soil and/or water samples.
6. Analyze the soil and/or water samples.
7. Using the selected receptor models, and the laboratory data, estimate the critical load for each sample. Provide an estimate of the critical load for each soil type/land use/aquatic unit using appropriate statistical methods.
8. Provide a recommendation and rationale regarding the most appropriate receptor model to be used for determining critical loads for the soil type/land use/aquatic units investigated.

The results of this study will be integrated into the review of the Acid Deposition Management Framework (Clean Air Strategic Alliance and Alberta Environment 1999), and updating of the analysis of acid deposition and acid deposition effects in Alberta, scheduled for 2004.

2.0 CRITICAL LOADS AND APPROACHES TO THEIR DERIVATION

The evolution of the critical load concept is discussed in Bull (1991). The critical load approach has been applied principally to the acidifying effects of sulphur and nitrogen on soils, waters and other receptors. The critical load approaches and mapping programs are most extensively developed in Europe, and are described in publications by Downing et al. (1993), Posch et al. (1995, 1997) and Task Force on Mapping (1996). The applicability of critical loads in Alberta has been discussed in Maynard (1996) and Schindler (1996). Based upon these two reports, critical loads have become the foundation of Alberta's Acid Deposition Management Framework (Clean Air Strategic Alliance and Alberta Environment 1999).

2.1 Critical Load Definition

The concept of critical loads has been adopted in various countries, especially those of the European Union, as a method for development and implementation of control strategies for air pollutants. In Europe, critical load had been defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (UN/ECE 1992). The critical load for acidic deposition to soils has been defined as 'the highest deposition of acidifying compounds that will not cause chemical changes in the soil which will lead to long-term harmful effects on the structure and function of the ecosystem' (Nilsson and Grennfelt 1988). Substituting 'surface waters' for 'soil' in this definition provides a definition with respect to aquatic ecosystems. The term critical load is defined in Alberta as 'the highest load that will not cause chemical changes leading to long-term harmful effects on the most sensitive ecological systems' (Clean Air Strategic Alliance and Alberta Environment 1999). Regardless of the definition, the critical load represents the level of sustained deposition of a substance that will not cause long-term harmful change to an ecosystem. It is thus a property of the ecosystem.

2.2 Critical Chemical Criteria and Critical Chemical Values

The process to establish critical loads depends upon the selection of critical chemical criteria. For soils, these criteria are chemical parameters such as pH, base saturation, aluminum (Al) concentration in soil solution, base cation (BC) concentration in soil solution, and the ratio of BC to Al concentrations. Any or all of these may be selected, and critical loads based upon the inputs chosen may be derived. For water the process is similar, with acid neutralizing capacity (ANC) being the most common critical chemical criterion used.

For each critical chemical criterion, critical chemical values must be established (Sverdrup et al. 1990). Critical chemical values are frequently referred to as thresholds. The criteria selected for this study and the rationale for each selection, and the critical chemical values (thresholds) assigned to each criterion, are discussed below.

2.2.1 *Soil pH*

Soil pH is defined as the pH of a solution in equilibrium with soil. It is determined by means of a glass, quinhydrone, or other suitable electrode or indicator usually using distilled water or a salt solution at a specified soil-solution ratio. Various methods can be used to measure soil pH; those particularly relevant in acid deposition impact evaluations are as follows:

pH(H_2O) - a soil sample is made into a paste with distilled water, and the pH measured by insertion of an electrode into the paste;

pH($CaCl_2$) - a soil sample is mixed in 0.01M $CaCl_2$ at a 1:2 soil:solution ratio (w:v), and the pH is measured with a glass electrode dipped into the solution;

pH(paste) - a saturated paste of soil in water is filtered, and the pH of the filtrate is measured with a glass electrode; and,

pH(solution) - soil solution is extracted in *situ*, and the pH of the solution is measured with a glass electrode.

Theoretically, the pH (solution) measure provides the most realistic indication of the pH environment of plant roots. However, pH (solution) is the most difficult to obtain due to the need for *in situ* extraction equipment and due to the time required to obtain sample for the pH measurement.

The closest estimates of the pH of solution *in situ*, particularly for soils having low soluble ion content, as reflected by low electrical conductivity are provided by pH (H_2O) and pH (solution) (Hendershot et al. 1993). However, accuracy and reproducibility by these methods are difficult to attain because of various factors that can affect the measurement, including soil:solution ratio, position of the measuring electrode, drying of soil, CO_2 concentration, and others. The value obtained may thus not reflect the actual pH of soil solution, however, close estimates of the pH in the root environment can be obtained by controlling some factors, particularly the soil:water ratio (e.g., 1:2 weight:volume).

The pH of soil sample suspended in 0.01 M $CaCl_2$ solution at a fixed soil:solution ratio is a commonly used method to characterize soil pH. This method has several advantages over pH (H_2O), among them being reproducibility even with dried soil samples. The salt solution generally results in a pH value about 0.5 units lower than that determined in water. Thus, it underestimates the soil solution pH, although it has also been considered to more accurately estimate the pH at the surfaces of soil particles because the weak salt solution simulates the soil electrolyte concentration adjacent to these surfaces. pH ($CaCl_2$) expresses a relationship between hydrogen and other cations in the soil solution (Bache 1980). Thus, it is responsive to changes in the concentrations of base cations relative to hydrogen, and as such can be useful in monitoring because it would decrease as base cations are lost from soils. Miewes et al. (1986) also noted that pH($CaCl_2$) is the more appropriate pH measure for characterizing the buffer range of a soil. Measurement of pH($CaCl_2$) is most commonly applied at

a 1:2 soil:solution ratio (Kalra and Maynard 1991). The pH($CaCl_2$) and pH(H_2O) measures are most commonly used in research and reported in the literature. Different soil acidification models use different pH measures. Consequently, it is important to indicate which measure is used.

Ulrich et al. (1984) suggested that a soil pH(H_2O) of 4.0 to 4.2 posed a high risk of damage to forest ecosystems, and that there was some risk at pH(H_2O) values greater than 4.2. Low soil pH is typical of forest soils, but is relatively uncommon in grassland soils. Chernozemic soil pH values are typically in the range of 5.6 to 7.7 (Turchenek et al. 1987). Soils in the range of pH (H_2O) 5.6 to 6.0 are sufficiently acidic to cause serious loss in yields of most crops in Alberta (Penney et al. 1977; Hoyt et al. 1981). Loss of crop productivity in acidic soils is due to reduced availability of some plant nutrients, metal element toxicity's, and restriction of nitrification and nitrogen fixation by micro-organisms (Hoyt et al. 1981). Rhizobia in particular are sensitive to soil pH (H_2O) below about 6.0 (Visser et al. 1987). These observations suggest that the critical chemical value for pH (4.0 to 4.2) for forest soils is not appropriate for application to cultivated soils. Furthermore, the typical range in Chernozemic soil pH values would suggest that the forest soil criteria are also not appropriate for Chernozemic soils under native grassland. Because pH values below 5.6 represents the lower limit of pH values associated with a Chernozemic soil, and a reduction in pH below 5.6 could trigger changes in microbiological and plant species composition, the critical chemical value for pH (H_2O) is set at pH 5.6. This is equivalent to a pH ($CaCl_2$) of about 5.0.

2.2.2 *Calcium to Aluminum (Ca:Al) and Base Cation to Aluminum (BC:Al) Ratios*

Different threshold levels of Al^{3+} related to plant health have been suggested (Bloom and Grigal 1985; Ulrich et al. 1984; Levine and Ciolkosz 1988); however, Cronan and Grigal (1995) indicated that although total concentration of Al in soil solution might appear to be the most straightforward index of potential Al toxicity to plants, this measure usually fails to be closely related to plant health. This may be due to the differential toxicity of the various Al species and to the ameliorative effects of other ions in solution. Reported Al toxicity thresholds for trees have a wide range, from <40 µmol L^{-1} to >3,000 µmol L^{-1}. However, toxicity has been shown within a much narrower range in terms of the Ca:Al molar ratio (range of 0.2 to 2.5), and risk thresholds are therefore more appropriately indicated in terms of this latter measure.

Cronan and Grigal (1995) reviewed Ca:Al ratios and other properties as indicators of stress in forest ecosystems and suggested a multiple assessment approach for determining the probability of suffering Al stress. The suggested threshold Ca:Al molar ratio of 1 (Table 1) is commonly applied in setting critical loads for forest soils in European countries (Warfvinge et al. 1992; de Vries 1993). Little information is available with respect to the significance of Ca:Al ratios in grassland soils, although the same critical chemical value (Ca:Al of 1) has been applied to various types of ecosystems in critical load determinations in Europe (Posch et al. 1997). In some countries, the BC:Al ratio is applied instead of Ca:Al because of work showing that BC:Al correlates more

strongly with plant root or shoot damage than Ca:Al. The term 'BC' in this expression refers to the sum of the molar concentrations of the cations Ca, Mg and K.

Sverdrup and Warfvinge (1993) presented a data compilation from the literature showing response curves of growth of various tree and ground vegetation species in relation to the BC:Al ratio. The BC:Al ratios at which growth of various grass species was negatively affected ranged widely from 0.3 to 300. Of the species listed, only Kentucky bluegrass (*Poa pratensis*), an introduced species, is found in Alberta grasslands. This species is listed as having a critical BC:Al ratio of 250. Some grasses of the same genus as those found in Alberta (*Festuca, Bromus, Agrostis*), and some *Carices*, have ratios ranging from 1 to 45. Only species of the *Poa* genus have BC:Al ratios of 250 or greater, while the maximum ratio for all other species is 45. Sensitivity of species of the *Festuca*, *Poa* and *Bromus* genus to pH and Al has also been found by Edmeades et al. (1991).

In the absence of research specific to grasslands in western Canada, it is difficult to select an appropriate BC:Al ratio that would be protective of all species. The ratio applied to forest soils of 1.0 appears to be low for grass species. The median value for the range of grasses reported by Sverdrup and Warfvinge (1993) is about 10. Considering that the critical value is less than 45 for most species, a value of 45 is selected for evaluation of acidification effects in the Provost-Esther study area. However, for purposes of comparison with this suggested critical chemical value for BC:Al, the examination of critical loads in this study includes derivations of critical loads using ratios of 1, 10 and 250.

Table 1. Critical Chemical Criteria (Indicators) and Critical Chemical Values (Thresholds) of Stress in Forest Ecosystems[1]

Measurement Endpoint (Critical Chemical Criteria)	Threshold (Critical Chemical Values)
Soil percent base saturation	<15% of effective CEC
Soil solution Ca:Al molar ratio	1.0 (50% risk) 0.5 (75% risk) 0.2 (95-100% risk)
Fine root Ca:Al molar ratio	0.2 (50% risk) 0.1 (80% risk)
Foliage (current year) Ca:Al molar ratio	12.5 (50% risk) 6.2 (75% risk)

1 -After Cronan and Grigal (1995)

2.2.3 Base Saturation Percentage

Soil percent base saturation was identified by Cronan and Grigal (1995) and by Miewes et al. (1986) as important in evaluating potential acidification stress on forest ecosystems. While there are various methods of measuring base saturation, the method relevant to threshold limits is based on percent of

'effective cation exchange capacity'. Effective cation exchange capacity (CEC) is defined as the CEC that occurs at field pH, as opposed to CEC measured at a specified pH (i.e., using a pH buffered extractant). Effective CEC is measured by extraction of exchangeable cations using a neutral, unbuffered saturating solution such as NaCl, KCl, $BaCl_2$ or NH_4Cl. The effective CEC quantifies the number of negatively charged sites with which cations are associated; the major cations in most soils are Ca, Mg, K, Na, Al, Fe, Mn and H. Thus;

$$CEC = Ca+Mg+K+Na+Al+Fe+Mn+H \text{ (expressed as cmoles charge per kg)} \quad (1)$$

$$\text{Base Sat \%} = (Ca+Mg+K+Na) \times 100 / (Ca+Mg+K+Na+Al+Fe+Mn+H) \quad (2)$$

Ca, Mg, K and Na are categorized as basic cations because the reaction between an exchangeable cation and free H^+ derived from dissociation of water results in generation of hydroxyl (OH^-). Al, Fe and Mn, on the other hand are categorized as acidic cations, as they react and tie up OH^- from H_2O, resulting in release of an equivalent amount H^+ (McBride 1994).

The measurement of CEC and base saturation according to equations (1) and (2) rely on measurement of each of the individual cations. An independent measure of CEC can also be obtained. When unbuffered NH_4Cl, or other neutral salt solution, is passed through a soil sample, NH_4^+ displaces the exchangeable cations. The NH_4^+ on the exchange complex is then replaced by Na by passing a NaCl solution through the sample, and the amount of NH_4^+ is measured, the quantity of NH_4^+ being equal to the CEC. Base saturation is then calculated as:

$$\text{Base Sat \%} = (Ca+Mg+K+Na) \times 100 / (CEC) \quad (3)$$

Base saturation can also be calculated from an independent estimate of the portion of the exchange attributable to acid cations (Al, Fe, Mn and H). This measure is referred to as the Exchangeable Titrateable Acidity (ETA). Base saturation is then calculated as:

$$\text{Base Sat \%} = (Ca+Mg+K+Na) \times 100 / (Ca+Mg+K+Na) + ETA \quad (4)$$

All of the above approaches theoretically provide the same base saturation value, although they seldom do so in practice. Different methods are applied in different institutions and countries. The protocol of the UN/ECE International Cooperative Programme on Integrated Monitoring on Air Pollution Effects applies methodology according to equation (4) above, although the other approaches are used in other programs (e.g., Miewes et al. 1986).

For forest ecosystems, a threshold base saturation reduction to a level of 5% (a critical chemical value of 5% base saturation) was suggested by Ulrich et al. (1984), while a reduction to 15% (Table 1) was recommended as a threshold by Cronan and Grigal (1995) on the basis of work by Cronan and Schofield (1990). These threshold values refer to base saturation calculations based on

'effective cation exchange capacity'; that is, cations are measured in an extract from a soil sample equilibrated with a neutral salt solution rather than a buffered solution (i.e., Equation 1).

Low base saturation is a characteristic of forest soils, and forest soils typically have relatively low pH values. Grassland soils, however, are characterized by relatively high base saturation and pH values. Chernozemic soils are the most common grassland soils, with Solonetzic and Vertisolic soils being common associates. A Chernozemic 'A' horizon is diagnostic for the Chernozemic Order of soils in Canada (Soil Classification Working Group 1998). Among the criteria associated with a Chernozemic A horizon is a base saturation greater than 80%, and Ca is the dominant exchangeable cation (other criteria apply to Chernozemic soils, but they are not associated with acidification). This 80% base saturation level is based on measurement by the 'neutral salt' method.

On the Canadian Prairies there is a gradual change in the nature of surface soil horizons from grassland soils in the south to forested soils in the north, where leached (Ae) horizons become more prevalent. A leached Ae horizon is indicative of loss of base cations and decreased pH in this horizon. There is thus a relationship between vegetation and the type of surface soil, the implication being that vegetation changes as pH and base saturation decrease. Climate, however, is another major factor that prevents grasslands on the dry prairie from converting to forest vegetation if they become acidified. It might be hypothesized, however, that prairie vegetation assemblages would change in response to acidification, such that more acid tolerant species may become more prevalent. On this basis, therefore, a base saturation of 80% was applied as a threshold limit for acidification of grassland soils. In summary, the justification for selection of this threshold is that (1) vegetation species composition could change, and (2) a soil would deviate from the Chernozemic class of soils if base saturation in the surface soil decreases below 80%.

2.2.4 *Acid Neutralizing Capacity (ANC) of Aquatic Systems*

Acid neutralizing capacity (ANC) is the ability of a solution to neutralize inputs of strong acid to a pre-selected equivalence. It is calculated as:

$$[ANC] = [BC] - [AN] = [HCO_3^-] = [A^-] - [H^+] - [Al^{n+}] \quad (5)$$

where, [BC] is the base cation concentration, [AN] is the strong acid anion concentration, $[HCO^{3-}]$ is the bicarbonate concentration, $[A^-]$ is the organic anion concentration and $[Al^{n+}]$ is the sum of all inorganic Al ions. A threshold (critical chemical value) for ANC of 20 $\mu eq\ L^{-1}$ has been applied in Scandinavia as a critical chemical value for fish in surface waters (Henriksen et al. 1990), although different ANC values specific to different receptors have also been suggested (Henriksen et al. 1995). The threshold is applied in models used to determine critical loads for surface water bodies; e.g., the Steady State Water Chemistry model and the First-Order Acidity Balance model (Task Force on Mapping 1996).

2.2.5 *Summary*

The threshold or critical chemical value refers to the value of a critical chemical criterion or combination of criteria (e.g. ratios) above or below which no harmful response in a biological indicator is expected occur. The critical chemical values pertinent to grassland soils and to surface waters that are used in this study are given in Table 2.

Table 2. Proposed Indicators and Thresholds of Stress in Grassland Ecosystems

Critical Chemical Criteria (Indicators)	Critical Chemical Values (Thresholds)
Soil	
pH($CaCl_2$)	5.0
pH(H_2O)	5.6 – 6.0
Base saturation percentage	80 %
BC:Al ratio	45
Surface water	
ANC	20 $\mu eq\ L^{-1}$

2.3 Empirical Method for Derivation of Critical Loads

Empirical methods of critical load derivation are based mainly on observation of responses of ecosystem components to acid deposition. In the case of soils, it has been suggested that a basic principle underlying a critical load is that the total input of hydrogen ions to the soil must not exceed the alkalinity produced by the weathering of soil minerals (Nilsson 1986). At a workshop in Skokloster, Sweden, it was concluded that the rate of chemical weathering is the single most important factor governing the soils ability to buffer incoming acidity, and therefore critical loads, for forest soils (Nilsson and Grenfeldt 1988).

This mineralogical approach (the Skokloster approach) was adopted with some modifications for critical load determination of soils in the U.K. (Hornung et al. 1995). Texture, drainage, soil thickness and other factors were considered in deriving critical loads in the U.K. Details of the application of this mineralogical approach to the Provost-Esther study area are presented in Section 6.1.

2.4 Use of Models to Derive Critical Loads

Numerous models have been developed to examine soil acidification and to derive critical loads. Modelling approaches comprise two main categories referred to as 'steady-state methods' and 'dynamic modelling'. Within each category, there are varying degrees of sophistication ranging from simple calculations to complex mathematical constructs. The most complex are integrated forest soil

models that link soil processes to other processes such as vegetation growth, hydrology and nutrient cycling.

Steady-state models calculate deposition levels that avoid harmful effects in ecosystems in steady-state (Task Force on Mapping 1996). Processes such as cation exchange and sulphate adsorption have a finite time scale and therefore cannot be included in steady-state models. Therefore, steady-state models are mainly used for calculation of critical loads over very long periods of time. Two types of steady-state models have been developed for soils. One-layer models, such as the Steady State Mass Balance (SSMB) model consider the soil as a single layer, whereas the multi-layer models consider chemical conditions in different soil layers or horizons. The one-layer SSMB model has been the most commonly applied tool for derivation of critical loads of soils in Europe (Task Force on Mapping 1996).

Dynamic models are a family of more complex models that use various calculations to simulate changes in soil solution or water chemistry due to acid deposition over time. Calculations of critical loads using these models is not as straightforward as with steady-state models because of the temporal aspect; i.e., it is necessary to determine the acceptability or non-acceptability of chemical changes in soils or waters in relation to a predetermined period of time. Another reason for non-usage is the need for much data required to run dynamic models. Consequently, dynamic models have not been used to a great extent in determining critical loads. However, these models are useful in scenario analysis; i.e., for assessing effects of given deposition levels over a selected period of time, and for determining the effects of different emission abatement strategies.

The availability of data is a major consideration in determining the method to be used for critical load determination. This factor generally limits the methods to empirical methods or to steady-state and the simpler dynamic modelling approaches.

3.0 REVIEW OF SOIL AND WATER ACIDIFICATION MODELS

Soil and water acidification models are reviewed in this section and their suitability for application in the Provost-Esther study area is assessed. In spite of a large number of models developed, most have limitations in terms of application to soils in Alberta. To be suitable for derivation of critical loads in the Provost-Esther study area a model must meet the following criteria:

1. The model must be relatively simple, requiring few data inputs for execution: Detailed soil chemical data are available for very few sites in Alberta, and application of the more complex models would require a major data collection effort that is beyond the scope of this study.

2. The software and documentation must be available: Details regarding sources are not provided in the literature for many models, and are not available in many cases. In some cases. the modelling can only be carried out by the developer of the model.

3. The model must be applicable in derivation of critical loads: Although they may be used to estimate critical loads, some models have been developed for other purposes such as an examination of ecosystem processes. Often, these models would require adjustment for critical load determination. This is especially true of the more complex models developed for forest growth analysis. Adjustment of model software is beyond the scope of this study.

3.1 Steady-state Models

Steady-state models are those in which all processes that vary over time are ignored and only long-term average fluxes are considered. Sverdrup et al. (1990) referred to the steady-state method more specifically as the 'steady-state mass balance method' since it uses the static mass balance between long-term inputs of acidity and long-term, in-soil production of alkalinity. The approach can be applied to soils, groundwater, lakes and surface water runoff from catchments.

Steady-state methods consider only the final result of a certain deposition level and do not consider the time frame within which that result is reached. The methods are based on the chemical and geochemical properties of soils and an understanding of the major processes involved in production and consumption of acidity in the soils. Mineral weathering is considered to be the major long-term source of alkalinity that neutralizes acidity in the soil system, as well as the major source of base cations to replace those removed by leaching.

The basic principle of the steady-state method involves identifying the long-term average sources of acidity and alkalinity in the soil system. Several assumptions have been made in the steady-state calculations: 1) ion exchange is at steady-state and there is no net change in base saturation or no net

transfer of acid neutralizing capacity from soil solution to the ion exchange complex; 2) there is no net denitrification, and adsorption or desorption of nitrogen; i.e., the nitrogen cycle is at steady-state; 3) sulphate is also at steady-state, there being no significant change in sulphide oxidation, sulphate uptake, sulphate fixation or sulphate reduction; 4) a simple hydrology is assumed and there is only direct infiltration of moisture through the soil profile, and; 5) there is soil solution equilibrium at all times (Sverdrup and Warfvinge 1988; Sverdrup et al. 1990).

The steady-state methods are used to calculate critical loads in terms of all sources of acidity to the receptor against all sinks for acidity plus sources of alkalinity. This can simply be expressed as: acid input equals soil acidity sinks plus base saturation change. Applying this balance at steady-state implies that there is zero base saturation change. Therefore acidity input is balanced only by soil acidity sinks, which consist mainly of (1) weathering and (2) loss of acidity by leaching into the lower soil layers (Sverdrup and de Vries 1994). The critical load is calculated by determining the weathering rate and setting chemical parameters of the leachate to critical, or threshold, values. Sverdrup et al. (1990) described three steady-state models developed in Europe – the SMB model, the PROFILE model and the MACAL model.

Simple Mass Balance (SMB) Model

The Simple Mass Balance model is calculated manually and can be used for quick evaluation of scenarios involving relatively higher and lower levels of acid deposition and neutralizing capacities to arrive at critical loads. This is a one-layer model wherein only a specified thickness of the soil profile can be considered. Details are presented in Section 6.2.1.

Critical load determination by the SMB model is directly dependent on the weathering rate, which is the major long-term source of alkalinity that neutralizes acidity in the soil system and the major source of base cations for replacing those removed by leaching. Thus, confidence in the critical load determined by this method depends on the level of confidence in the model input value for the weathering rate. Most estimations of weathering rate are based on correlations of experimentally determined weathering rates with soil type, mineralogy, base cation content or texture. Others are based on computations using soil mineralogy, wherein quantitative data for the complete suite of minerals present in a soil are required. The approach has been widely used in Europe to provide a weathering term for input into the SMB equation (Task Force on Mapping 1996).

Another approach to estimating weathering is based on an estimation of mineralogy from total chemical analysis of soil by use of the UPPSALA model which performs a stepwise allocation of elements (Ca, Mg etc.) to different soil minerals. Minimal data needed by the UPPSALA model for converting elemental contents to mineralogy are levels of total Na, K, Ca, Mg, P, Al, Si and Fe (Sverdrup 1990).

The SMB approach is applicable in Alberta in terms of the three criteria of simplicity, availability and applicability in critical load derivation. Critical loads can easily be calculated for an individual soil, or a large number of computations can be made within a spreadsheet. The SMB model was applied to the Provost-Esther study area using a weathering rate estimated from information in the literature as described in Section 6.2.1.

Regional PROFILE Model

PROFILE is a multi-layer, steady-state model that can calculate critical loads from chemical weathering of soil minerals, uptake of base cations, ammonia and nitrate by vegetation, nitrification of ammonia to nitrate, and solution chemistry involving the carbonate system, Al species and organic acids. The PROFILE model uses a geochemical modelling approach whereby weathering rates are calculated from soil mineralogical data. Deposition of sulphate, ammonia, nitrate and base cations are model inputs. Soil processes are represented by mass balance for acid neutralizing capacity (ANC), base cations, nitrate and ammonia, and by kinetic equations for weathering and nitrification. Further details about the model can be found in Warfvinge and Sverdrup (1992) and Sverdrup et al. (1992).

Applicability of the PROFILE model in Alberta is limited only by the lack of mineralogical information which is a necessary model input. The model program itself is readily available. An alternative to the use of mineralogy involves mineralogy estimation using the UPPSALA model (Sverdrup 1990). The application of the PROFILE model is nevertheless not possible as the required total elemental analysis was not available and could not be accommodated in this study of the soils in the Provost-Esther study area.

Model to Assess a Critical Acid Load (MACAL) Model

MACAL is a multi-layer, steady-state model similar to PROFILE (Sverdrup and Warfvinge 1988; de Vries 1988). The weathering rate is an input parameter to MACAL, whereas PROFILE generates this from mineralogy and texture. MACAL also differs from PROFILE in that the internal cycling of nutrients in the system is included. MACAL, however, has not been applied to critical load derivation since about 1988. It is thus assumed that this model is not available for general use.

3.2 Dynamic Models

Dynamic models are used to calculate the acidification process for an ecosystem through time. Dynamic models, as compared to steady-state models, require more input data of which several parameters are more difficult to obtain. Since an assessment of the time periods involved in acidification responses and recovery from acidification can be made with these models, they are the best tools available for addressing time-dependent scenarios and the impact of episodic events on

ecosystems. Several of the models listed here are research tools, and are not available for evaluation and application in Alberta at the present time.

The gradual change with time in the acidification state of the system in response to some change in deposition is calculated with dynamic models. Critical loads can be calculated from different deposition scenarios, and the results can be compared to the critical chemical values (thresholds) for several different critical chemical criteria (e.g. ion exchange, weathering of soil minerals, uptake and cycling of base cations and nitrogen by plants, and soil solution equilibrium chemistry) in the system simultaneously. They use integrated mass balances for substances and differential equations for the rates of different processes. The time-dependent scenarios are obtained by numerical integration of the model subroutines advancing in small time-steps.

Various assumptions are made in the equations within the dynamic models. It is generally assumed that the CEC is constant over time and that a certain ion exchange equilibrium applies (Gapon or Gaines-Thomas), and aluminum is assumed to be in continuous equilibrium with a mineral of the same composition as gibbsite (de Vries 1991). Some models assume sulphate adsorption to be negligible or at steady-state, while others have sulphate adsorption as a major process.

Some soil models are subroutines of more complex models used for impact studies and critical load determinations for aquatic systems. Sverdrup et al. (1990) suggested that several models be examined before choosing a model for soil evaluations and critical load calculations. The models differ somewhat in their basic principles, and have different limitations connected to their use and to the interpretation of their results. Such factors must be carefully studied before a model is chosen for a specific type of system. Brief descriptions of some currently used dynamic models are provided below.

Model of Acidification of Groundwater in Catchments (MAGIC), Model of Acidification of Groundwaters In Catchments - With Aggregated Nitrogen Dynamics (MAGIC-WAND) and Model for Ecosystem Retention and Loss of Nitrogen (MERLIN)

The MAGIC (Model of Acidification of Groundwater in Catchments) family of models increases in complexity from MAGIC through MAGIC-WAND (Model of Acidification of Groundwaters In Catchments--With Aggregated Nitrogen Dynamics) to MERLIN (Model for Ecosystem Retention and Loss of Nitrogen). MAGIC (Cosby et al. 1985) combines various soil chemical processes at a catchment scale to simulate soil and surface chemistry. The soil processes include soil-soil solution equilibrium equations involving sulphate sorption, cation exchange, dissolution and precipitation of aluminum, and dissolution of inorganic carbon. Mass balance equations for fluxes of major ions to and from soils and surface waters are governed by atmospheric inputs, mineral weathering, net uptake in biomass, and loss in runoff. The MAGIC model is generally used as a one-box model (Cosby et al. 1985; Hornberger et al. 1987) using average soil profile chemistry as inputs, and the

compartment is assumed to be continuously mixed, homogeneous, and of constant density. The model ignores the nitrogen cycle.

MAGIC-WAND is an extension of the MAGIC model that incorporates the major nitrogen fluxes and changes through time. The model was mainly designed to enable assessment of future surface water chemistry responses to nitrogen inputs (Ferrier et al. 1995, in Task Force on Mapping 1996).

MERLIN requires detailed information describing nitrogen and carbon fluxes in the ecosystem (Ferrier et al. 1995, in Task Force on Mapping 1996). It is data intensive, although a general model is being developed for regional application.

The MAGIC model may be applicable to evaluation of soils in Alberta. It requires a weathering rate as model input, along with other basic soil parameters. However, due to the cost associated with acquiring MAGIC, it was not used in this study. The MAGIC-WAND and MERLIN models are data-intensive and, therefore, are unsuitable for application in the study area.

Simulation Model for Acidification's Regional Trends (SMART), Regional Air Pollution Information and Simulation (RESAM) and Nutrient Cycling and Soil Acidification Model (NUCSAM)

SMART (Simulation Model for Acidification's Regional Trends) is used inside RAINS (Regional Air Pollution Information and Simulation model), which is a comprehensive model for examining various ecosystem and emission scenarios in Europe. SMART is a one-layer model, and has many similarities to the MAGIC model (de Vries and Kros 1989; de Vries et al. 1989; de Vries 1994). MAGIC and SMART have been applied extensively in Europe to examine soil influences in catchments and lakes. They are among the least input-data-intensive of the dynamic models, due to various simplifications in the equations used to represent the nitrogen cycle and water flux. SMART also assumes the sulphur adsorption to be at steady-state. Ion exchange in MAGIC and SMART are based on the Gaines-Thomas equations (de Vries 1994).

RESAM (Regional Soil Acidification Model) is a multi-layer model and is therefore more complex than SMART (de Vries and Kros 1989). RESAM is a comprehensive model, incorporating many processes such as nitrogen and base cation cycling between the soil and the canopy, biomass mineralization, and cation exchange equilibrium and flux mass balances for the soil profile. Cation exchange in the model is based on the Gaines-Thomas equations. The main parameters considered within the model are aluminum, base cations and nitrogen. The weathering rate is modelled by applying research which shows a correlation between weathering rate and total soil base cation content (de Vries and Kros 1989).

NUCSAM (Nutrient Cycling and Soil Acidification Model) is the most complex of the SMART family of models. It processes data in one-day time increments, requires more data than the other

models, and is suitable for evaluation of effects on an individual site basis. It has been coupled with FORGRO (Forest Growth Model) for examining acidification effects in terms of tree growth and nutrient dynamics (Tiktak and van Grinsven 1995).

The SMART model is the most easily applied of the above models. It was readily available and was applied to soils of the study area. RESAM was not used, and although it has higher data input requirements, it may be applicable in Alberta. NUCSAM is not applicable due to its substantially greater data inputs.

Soil Acidification in Forest Ecosystems (SAFE)

SAFE (Soil Acidification in Forest Ecosystems) is the dynamic counterpart of the steady-state PROFILE model and uses the same input data and weathering rate sub-model as PROFILE (Warfvinge et al. 1993). The model uses time series data for deposition, uptake, hydrology and climate to calculate changes in soil solution chemistry and soil base saturation over time. It is a multi-layer model and is generally applied using yearly averages for inputs and outputs. SAFE is more complicated than PROFILE and requires data on forest stand history, present biomass and nutrient content in tree components. It would have to be substantially adjusted to fit a grassland application. This, in addition to being data-intensive makes it unsuitable for application in the Provost-Esther critical loads evaluation.

MIDAS

MIDAS is a one-layer model, based on acidity as the main variable, and is similar in structure to SMART and MAGIC (Holmberg et al. 1989). The model focuses on ion exchange processes, using either the Gaines-Thomas equilibrium ion exchange approach or an optional kinetic approach. The weathering rate is set at a constant level. The model ignores the nitrogen cycle. The MIDAS model may be applicable to calculation of critical loads in Alberta, but its availability is unknown and it therefore could not be included in this study.

Forest Sustainability (FORSUST)

The SMB approach was applied in deriving critical loads for forest soils in southern Ontario by Arp et al. (1996). This SMB approach was modified and extended to evaluate potentially sustainable forest biomass production levels (Bhatti et al. 1998). The resulting ForSust (Forest Sustainability) model simulates tree biomass growth based on nutrient inputs from estimated atmospheric acid deposition (N, Ca, Mg and K) and soil weathering (Ca, Mg and K), and matches the resulting nutrient supply rates with calculated nutrient demand. Nutrient demand is based on nutrient concentrations in wood, bark, branches and foliage, which are model inputs. The sustainable export rates for base cations are defined by mean annual increment and biomass harvest (or loss due to fire). Along with nutrient leaching, based on hydrological characteristics, critical loads can be calculated

by the SMB approach (embodied within ForSust) wherein the long-term export of base cations must be balanced by replenishment through mineral weathering.

The ForSust model has previously been applied in Alberta in evaluation of critical loads in the oil sands area (Arp and Doram 1998). All of the required data were not available for the individual sites modelled; however, approximations based on other studies were applied. The application to a grassland situation would require an evaluation of nutrient export, which as discussed in Section 6.2.2 would essentially be close to nil due to annual dieback of grasses and little export in the form of animal biomass. Other model inputs are relatively simple, comprising base cation, phosphorus and pH data for soils, and acidic and base cation data for atmospheric deposition. The ForSust model may thus provide utility in Alberta due to these simple input requirements. However, access to the model program was not possible in time for inclusion of the ForSust model in the estimation of critical loads in the Provost-Esther study area. This is an item for future consideration.

BLOOM-GRIGAL Model

The BLOOM-GRIGAL model is a semi-empirical model for predicting changes in soil pH, base saturation, and solution Al levels resulting from acidic precipitation. The changes can be calculated over specified periods of time. The model is based on acid buffering by cation exchange, while at the same time calculating base cation replenishment by weathering. Nutrient cycling is not considered except in the sense that it is assumed to be in a steady-state, and therefore does not influence any of the soil properties that are affected by acidification. A major strength of the model lies in its use of readily available data, thus enabling its regional application (Bloom and Grigal 1985).

The Bloom-Grigal model was applied in Alberta for examination of acid deposition scenarios in the Acid Deposition Research Program (Abboud and Turchenek 1989), and has since been modified and applied in various studies. This modified model is referred to as the ARC Model.

Alberta Research Council (ARC) Model

The ARC model is derived from Bloom and Grigal (1985) and incorporates empirical relationships for cation exchange and pH based on Alberta soil properties. The model has been described by Abboud and Turchenek (1990) and Turchenek and Abboud (1988), and is described in part in Section 6 of this report.

Integrated Forest Soil Models

Sixteen forest-soil-atmosphere models were reviewed by Tiktak and Grinsven (1995). These models are primarily applied in studies of effects of environmental factors on forest growth, soil and groundwater quality, and surface water quality. Several of them can also be applied in derivation of critical loads. Many of these models are not available for use, or they have not been well

documented, while others are available and are well documented. Two of the models have been discussed in previous sections (PROFILE and MAGIC). The model ForM-S (Forest Model Series) is a group of soil, growth, climate and hydrology models related to the ForSust model. Except for PROFILE, MAGIC and the ForSust version of models developed by P. Arp and colleagues at the University of New Brunswick, all models are considered at this time as being unsuitable for critical load determinations, due primarily to high data requirements and/or to unavailability.

The full version of the ILWAS model also falls into the category of integrated models. Other complex models have been developed that were not reviewed by Tiktak and Grinsven (1995). These include ACIDIC (Kareinen et al. 1998) and NUCM (Nutrient Cycling Model, Johnson et al. 1993, 1995). Both of these models, while readily available, have extensive, detailed input requirements and are therefore considered unsuitable for derivation of critical loads in Alberta at this time.

Other Soil Acidification Models

Other models have been developed but have either not been applied extensively or have evolved into newer versions. The LEVINE AND CIOLKOSZ model (Levine and Ciolkosz 1988) is similar to the BLOOM and GRIGAL model, but incorporates additional subroutines to account for more of the processes influencing acidity, namely sulphate adsorption and formation and dissolution of sesquioxides in the soil profile. The model considers two layers whereby acidic deposition reactions are first calculated for the A horizon and the calculated soil solution composition is used as input for the B horizon (Levine and Ciolcosz 1988). The model is attractive in terms of its treatment of pedogenic horizons, but it does not appear to have been applied since its initial description by Levine and Ciolkosz (1988), and it could not be obtained for use in this study.

McFee et al. (1977) described a simple approach while Arp (1983) and Reuss and Johnson (1986) documented more complex models based on processes on the ion exchange complex and in soil solutions. The latter two models have evolved into the more complex ForSust and NUCM models, respectively. Geochemical models such as GEOCHEM (Sposito and Mattigod 1979) could be used for evaluations acid deposition effects on soils. However, the lack of availability of models specifically addressing acidification effects appears to have precluded the use of geochemical models in the derivation of critical loads.

ILWAS (Integrated Lake Water Acidification Study) is a complex model developed in the United States for examination of watershed and surface water acidification (Gherini et al. 1985). It has a multi-compartment soil module including: ion exchange equilibrium based on the Gaines-Thomas equation; equilibrium or kinetic aluminum dynamics; a canopy module including uptake of base cations and nitrogen; leaf exudation; litterfall and biomass degradation; a snowmelt routine; a 12-layer lake model, and; a kinetic module for nitrification and denitrification. The weathering rate is a model input, and it is varied with soil pH. The model is generally applied in studies of acidification

scenarios and not for critical load determination. It has high data input requirements and as such is considered unsuitable for application in this (Provost-Esther) study area.

3.3 Surface Water Acidification Models

The determination of critical loads of acidity to surface waters was an initial objective in determining critical loads in the Provost-Esther study area. However, the high salinity of lakes in the region results in very low acidification sensitivity. Thus, there was no effort made in determining the critical loads of surface waters in this area. Critical loads are currently being determined for a number of surface water bodies in northeastern Alberta using the Steady Sate Water Chemistry model (personal communication, D. Trew, Alberta Environment, Edmonton).

For future reference, possible modelling approaches to determining critical loads are listed below, with references:

- SSWC (Steady State Water Chemistry) model - (Henriksen et al. 1995; Brakke et al. 1990)
- FAB (First-Order Acidity Balance) Model – (Henriksen et al. 1993)
- MOSS (Modification of the Steady State) Method - (Shaffer et al. 1991)
- ETD (Enhanced Trickle Down) Model – (Eary et al. 1989)
- MAGIC (Model for the Acidification of Groundwater in Catchments) – (Cosby et al. 1985)
- ILWAS model (Integrated Lake Water Acidification Study) - Gherini et al. (1985)
- PULSE model (Bergstrom and Lindstrom 1989)
- BIRKENES model (Christophersen et al. 1982)

The above models are listed more or less in order of increasing complexity. In addition to these models, the Empirical Diatom Method, which correlates diatom assemblages in lake sediments to prior acidic conditions, has been applied in some European countries. Descriptions of the SSWC and FAB models, and the Diatom method, are given in Task Force on Mapping (1996). Reviews of a number of the models can be found in Eary et al. (1989) and Holdren et al. (1993). A feature of aquatic models is the requirement for estimates of runoff and soil percolation water flow within the watershed containing the water body under study. Application of these models thus requires delineation of watersheds and field measurement or estimates of water and elemental fluxes within the watersheds. These data requirements go well beyond the scope of this study.

3.4 Applicability of Models to Grassland Ecosystems

Most of the models discussed above are based on nutrient cycling principles, a main principle being that nutrient export must be balanced by nutrient supply (through weathering) to prevent changes in soil chemistry. The same principles apply in all soils. However, the soil acidification models described above were derived for application to forest ecosystems where the mechanisms of nutrient

export differ from those in grassland environments, particularly those grasslands used as range pastures as is the case in the Provost-Esther area. In pastoral systems, the main export is in the form of animal biomass. Otherwise, plant components die back annually and nutrients are returned to the soil system. The plant debris undergoes humification, the result being an organic matter-rich, dark-coloured topsoil. The system may be considered as being in a steady-state when organic matter additions equal losses due to mineralization. There is likewise a balance in nutrient supply and loss. For example, base cations are returned to the soil by organic matter decomposition, are also added to the system by weathering, and lost from the system by leaching. Thus, the steady-state concept applies to grassland soils as it does to forest soils, and with some adjustments, models developed for forest soils should be applicable to grassland soils.

The nutrient export component in native grassland soils used as rangeland can be considered as negligible to very low (see Section 6.2.2). In more intensively managed systems, nutrient export can be higher, and acidification can result from nitrate leaching and organic material accumulation. A conceptual model has been developed for pastoral systems in New Zealand (de Klein et al. 1997). The model provides a framework for quantifying three main components of soil acidification: (1) acidification induced by organic matter accumulation; (2) animal-induced acidification, through nitrate leaching and nutrient transfer, and: (3) fertilizer induced acidification, mainly through P and S application. The model predicted acidification rates for test areas reasonably well, thus verifying the importance of the above factors as acidifying agents. The model has not been developed as a computer program. Its main value is in demonstrating an approach to quantifying animal-induced acidification, and the integration with organic matter and fertilizer induced acidification. It is relevant to systems that are more intensively managed than those under consideration in the Provost-Esther study area.

3.5 Models Used to Derive Critical Loads for Soils in the Provost-Esther Study Area

The models described in previous sections were initially short-listed based on availability. The list included the SMB, SMART, ForSust, PROFILE, ARC, MAGIC, NUCM, and ACIDIC models. The SMB model is available for use in that the equations are well documented and calculations easily can be made for individual sites or by use of a spreadsheet for several sites. All other models are more complex and have been developed as computer programs.

The ACIDIC and NUCM models were excluded from the list on the basis of their complexity and large amount of data input parameters. They are more appropriate for site-specific detailed evaluations as opposed to application to numerous sites on a regional basis. The MAGIC model is available for a fee and could not be obtained for this project. The PROFILE model requires data for mineralogy or total elemental contents of soils. The acquisition of these data was beyond the scope of this study and this model could, therefore, not be applied.

In addition to the SMB model, only the SMART and ARC models were available and appropriate for application in the study area. Computer code for the ForSust model is not available, however, future application of this model could be carried out by collaboration with the model developers. In summary, models selected for determination of critical loads in the Provost-Esther study area are the SMB, SMART, and ARC models. In addition to these models, critical loads were also estimated by application of an empirical method based upon soil texture, an adjustment of the Skokloster correlation as applied in the UK.

4.0 METHODS OF DATA ACQUISITION AND COMPILATION FOR CRITICAL LOAD DETERMINATION

4.1 Baseline Soil Information

Information about the distribution and properties of soils in the Provost-Esther study area is available from soil survey reports and from the AGRASID database (CAESA Soil Inventory Working Group 1998). The AGRASID database provides soil survey coverage for the agricultural regions of Alberta, along with descriptions of soil series, including typical soil chemical attributes. Soil distribution is presented in the database within a hierarchical framework based on the national ecological framework for Canada (Ecological Stratification Working Group 1995). Details of ecological stratification and soil properties in the study area are presented in Sections 5.1 and 5.2.

Ecological stratification of the land begins with the highest level, the Ecozone, which is an area that is representative of large and very generalized ecological units characterized by interactive and adjusting abiotic and biotic factors. The Provost-Esther study area is within the Prairies Ecozone.

An Ecoregion is a part of an Ecozone characterized by distinctive ecological responses to climate as expressed by the development of vegetation, soil, water, fauna, etc. (Ecological Stratification Working Group 1995). The study area occurs within three Ecoregions, the Aspen Parkland at the north extremity, Moist Mixed Grass Ecoregion through the middle of the area, and the Mixed Grassland Ecoregion at the southern extremity. Dark Brown Chernozems are characteristic soils of those parts of the study within the Moist Mixed Grass and Aspen Parkland Ecoregions. Brown Chernozems are characteristic of the Mixed Grassland Ecoregion. Descriptions of the Ecoregions are provided in Appendix D.

An Ecodistrict is a subdivision of an Ecoregion in the ecological land classification hierarchy. It is characterized by distinct assemblages of landform, relief, surficial geologic material, soil, water bodies, vegetation and land uses (Ecological Stratification Working Group 1995). The soil mapping system in Alberta further subdivides Ecodistricts into Land Systems. A Land System is defined as a subdivision of an Ecodistrict that is recognized and separated by differences in one or more of: general pattern of land surface form, surficial geologic materials, amount of lakes or wetlands, or general soil pattern. All Land Systems within one Ecodistrict have the same general climate for agriculture, but differences in microclimatic pattern can be recognized. Soil Landscapes are subdivisions of Land Systems that display a consistent and recognizable pattern of distribution of soils and landscape elements (CAESA Soil Inventory Working Group 1998).

Soil types as identified at the Land System level were applied in developing a sampling protocol and critical loads map of the study area. Analysis of soil types at the Soil Landscape level of mapping would prove to be unwieldy due to the large number of delineations within one grid cell. Land Systems provide information at a lower level of detail, but at a somewhat greater level than that of

the land units that form the basis of soil sensitivity mapping by Holowaychuk and Fessenden (1987). Consequently, Land System information was considered to be a practical basis for refining the previous soil sensitivity mapping and for calculating critical loads.

4.2 Initial Acid Sensitivity Rating

Each Land System is characterized by an assemblage of dominant and subdominant soil series. The extent of each series was estimated from the attribute information provided in AGRASID. These were then allocated an acid sensitivity rating based on base loss, acidification, aluminum solubilization and overall sensitivity ratings using soil pH and cation exchange capacity as the major criteria (Holowaychuk and Fessenden 1987). The ratings were developed for the top 20 cm of soil.

Of the soil attributes described in soil surveys reports, texture would be considered as one that is frequently and reliably estimated in the field. One would place less confidence in chemical criteria such as pH and cation exchange capacity because the values reported are generally based on sampling and analysis of very few profiles. However, cation exchange capacity is strongly related to texture because of its dependence on the clay content of the soil. Thus, instead of applying the Holowaychuk and Fessenden (1987) sensitivity classification, soils in the Provost-Esther study area were assigned preliminary sensitivity ratings on the basis of texture alone. Soils of sand or loamy sand texture were characterized as being Sensitive to acid deposition. Soils of sandy loam texture were assigned a Moderate sensitivity rating. All soils of texture finer than sandy loam (including fine and very fine sandy loam) were assigned a Low sensitivity rating. As an example, a sandy soil with low CEC and a pH level of about 7 might be dominant in a particular land system. The Holowaychuk-Fessenden criteria would rate these as being of Low sensitivity, mainly due to the pH criterion. In this project, this soil was rated as Sensitive, or more accurately, 'potentially' Sensitive, based on the sandy soil texture alone, and ignoring the pH, to which relatively less confidence can be attributed.

The sensitivity rating allocation to Land Systems provided information about coverage of all potentially acid sensitive soils. This provided a framework for representative sampling of soils for the critical loads evaluation. Agricultural soils and native/range soils of Low sensitivity were excluded from the evaluation because (1) acid deposition management is to be based on the extent of sensitive soils affected (Clean Air Strategic Alliance and Alberta Environment 1999), and (2) these soils are generally under cultivation and subject to various management practices, particularly fertilization, which confound any evaluations of acidification due to atmospheric deposition.

The sensitivity ratings were re-evaluated upon completion of the critical load determinations, with allocations to sensitivity classes based on pH, base saturation percentage and base cation to aluminum ratio. These were compared with the criteria of Holowaychuk and Fessenden (1987), and a revised soil distribution and acid sensitivity map was produced for the study area.

4.3 Land Use Information

It had been determined early in the critical loads project in the Provost-Esther area that cultivated lands would be excluded from the study and that only uncultivated lands would be addressed. The main reasons, as indicated previously, are that cultivated soils are subjected to various practices such as fertilization and manure application, and these would complicate evaluations in relation to atmospheric acid deposition. Additionally, soils under cultivation are generally soils that have higher nutrient content and buffering capacity (base cations), and are therefore the least sensitive soils within any given area. Land use information was therefore required, in addition to soil and landscape information, to enable planning of a sampling program, and more importantly, to enable calculation of the areal extents of soils of different acid sensitivity.

Land use information was available from the Prairie Farm Rehabilitation Administration (PFRA) which had undertaken mapping for the purpose of verifying applications under the Western Grain Transition Payments Program (WGTPP). The WGTPP map was based on analysis of satellite images acquired from 1993 to 1995, and land cover was allocated to one of eleven classes:

1. Cultivated crop land – land that is annually seeded or under summer fallow;
2. Forage (hay) – land that is in perennial forage for hay or silage production (dominantly alfalfa);
3. Grasslands – land that is in perennial grasses and herbaceous species for grazing use including native range, seeded tame pasture, abandoned farm areas and other non-cultivated uses (ditches, riparian areas, etc.);
4. Shrubs – land that has perennial woody shrub coverage;
5. Trees – hardwoods, mixed woods, recent burns and cutovers;
6. Wetlands – intermittent water bodies, area that have semi-permanent or permanent wetland vegetation, including fens, bogs, swamps, sloughs, marshes, etc.;
7. Water – permanent water bodies including lakes, rivers, irrigation canals;
8. Non-agricultural lands – land that is dominantly in a non-vegetative or non-agricultural land use, including farmsteads, roads, cities, towns, open pit mines, industrial sites, etc.;
9. Clouds and shadow;
10. Mud, sand and/or saline areas; and,
11. Unclassified area – areas outside of the study area.

Areas classed as Grassland, Shrubs or Trees (categories 3, 4, and 5 above) were selected from the WGTPP digital database and superimposed on the initial soil and soil sensitivity map, the genesis of which is described in Section 4.1 above. All other land was regarded as tilled land, although minor areas of disturbed lands occurred as well. Spatial information about water bodies was then taken from a separate digital layer in the database to produce a combined soil/land use/surface water map.

The map developers at PFRA had indicated that there could be uncertainty in the classification of certain types of land, especially forages with natural grasslands. Upon carrying out the field sampling program in this project, the PFRA information was found to be highly accurate for sandy soil areas ranked as Sensitive to acid deposition. Sandy soil areas appeared to have been left in their native condition and were used as rangeland. Adjoining non-sandy soils are mainly used for production of annual crops. Areas ranked as having Moderate sensitivity were less accurately represented in the PFRA map, as it was found during the field sampling program that some areas indicated as Grassland were in fact cultivated. Appropriate adjustments to the sampling protocol were made (e.g. selection of non-cultivated sample location nearby).

4.4 Baseline Surface Water Information

Information about the distribution and extent of surface water bodies in the Provost-Esther study area was derived form the WGTPP information as indicated in Section 4.2. Detailed information about the areas of wetlands within the ecosystems of Alberta is available in 'Ecodistricts of Alberta: Summary of Biophysical Attributes' (Strong and Thompson 1995) and in 'Characterization of Wetlands in the Settled Area of Alberta (Strong et al. 1993). Information about shallow water bodies is included in the latter compilation, but lakes are not included. Water quality information is available in the form of a digital database maintained by Alberta Environment. The database presents values for pH, alkalinity, total dissolved solids and calcium for 1,156 Alberta Lakes, with information about additional lakes added on an ongoing basis (Saffran and Trew 1996).

4.5 Soil Sampling

The goals established for soil sampling to meet the needs of critical load determination were to obtain soil samples of the A and B soil horizons at 25-30 sites from the Sensitive and Moderate acidification sensitivity areas in the study region, and to obtain additional soil samples of the A and B horizons at the same 25-30 sites from different slope positions in order to determine the influence of landscape position on critical loads. Additionally, land use observations were made in order to verify the land use information from the WGTPP database.

The soil and soil sensitivity mapping activity resulted in identification of four Land Systems of potential Sensitivity, and three Land Systems of potential Moderate sensitivity to acidic deposition. These areas varied in size. More or less evenly distributed soil sampling locations were selected within these areas on lands designated as having Grassland, Bush or Tree cover. During field activities, it was found that many of the pre-selected sites were not accessible due to lack of roads, to fenced properties, and other reasons. In these cases, an alternate suitable site was selected within the same area. Forty-five sites were pre-selected, and of these, 27 sites were sampled. While sampling of soils in different slope positions was one objective of the sampling program, it was found that landscapes at most sites were gently undulating and no catenary differences were evident in the field.

Consequently, samples from different slope positions were taken at only five of these sites, which were characterized by relatively greater relief and slopes as compared to the majority of sites.

The soils were sampled by pedogenic horizon to a 50 cm depth. The 50 cm sampling depth was selected on the basis of the depth criteria of most of the soil acidification models. Soil samples were taken by excavating a small pit to at least 50 cm depth and taking about a kilogram of sample from each discernable soil horizon. In most cases, the soil could be separated only into an Ah and a Bm horizon. Soils under trees had litter layers and greater horizon differentiation, and samples of LFH, Ae and Bm horizons were taken from these. The samples were placed in plastic bags. The samples were taken during two trips, one in October and one in early November 1999.

Additional samples representing different landscape (slope) positions were taken at some of the sampling sites. This sampling scheme is based on the catenary concept of soil development which is especially well expressed in prairie landscapes. A catena is defined as a sequence of soils of about the same age, derived from similar parent material, and occurring under similar climatic conditions, but having different characteristics due to variation in relief and in drainage. The differences in relief and drainage commonly result in differences in thicknesses of A and B horizons, and possibly in their chemistry. Samples were taken to check for differences in soil properties, thus enabling more detailed evaluation of the acidification sensitivity of soils and of their critical loads in relation to landscape position. This would have implications regarding the percentage estimates of the areas with differing critical loads within the grid cell.

4.6 Water Sampling

Sampling of water from three surface water bodies was established as a goal for the field program. It was found, however, that most lakes in the study area appeared to be very shallow, or had dried out, and all were generally characterized by saline margins. A small group of connected lakes in the south of the area appeared to be deeper than normal, and one of these (easily accessible from a road) was selected for sampling. The lake is located in SE5-31-1-W4. One 500 mL sample was collected for analysis of a suite of water quality parameters. One 50 mL sample collected for NH_3-N determination was treated with 5% H_2SO_4 preservative. Samples were collected from the lakeshore using a pole of about 4 metre length, with the sample bottle attached to the end of the pole.

4.7 Soil and Water Chemical Analyses

Soil samples were analyzed for various properties as follows:

pH($CaCl_2$): By potentiometric measurement in a 1:2 (w:v) solid-to-liquid mixture of soil in 0.01 M $CaCl_2$. (Method 7 (ii) in Kalra and Maynard (1991). The soil-to-solution ratio for litter (LFH) material was 1:4.

pH (H_2O): By potentiometric measurement in a saturated paste (Method 7 (i), Kalra and Maynard (1991).

Calcium Carbonate Equivalent: Carbonates were dissolved by reaction with HCl and the evolved CO_2 was measured manometrically as described in Method 10 of Kalra and Maynard (1991), with the exclusion of timed measurements for differentiation of calcite and dolomite.

Total Carbon, Nitrogen and Sulphur: By combustion and automated detection using a Leco C-N-S unit. The total-C obtained was corrected for carbonate-C, if present, to obtain total organic-C. Samples with pH <7 were assumed to contain no carbonate-C, and, therefore, total-C equals total organic-C in these cases.

Cation Exchange Capacity (Neutral Salt): By 1.0 M NH_4Cl extractant (unbuffered), and measurement of NH_4^+ by distillation. The method is described in Method 15 (ii) in Kalra and Maynard (1991). The distillation step differed in that NH_4^+ is not displaced with Na, but the whole sample was distilled to determine content of adsorbed NH_4^+.

Cation Exchange Capacity (Buffered): By 1.0 M ammonium acetate extractant buffered at pH 7, and measurement of NH_4^+ by distillation. The method was applied as described in Procedure 3.3.2 in McKeague (1978), except that NH_4^+ was not displaced with Na, and the whole sample was distilled to determine the content of adsorbed NH_4^+.

Exchangeable ions: By Inductively Coupled Plasma (ICP) Atomic Emission Spectroscopy of the unbuffered CEC extract. Ions included in the ICP scan were Ca, Mg, Na, K, Fe, Mn and Al. Exchangeable H was estimated from the pH difference between the unbuffered NH_4Cl extractant before and after extraction.

Electrical Conductivity and Soluble Salts: By measurement of electrical conductivity and ions in the aqueous extract from a saturated paste of a soil sample (Method 8(i), Kalra and Maynard (1991). EC and pH were measured in the extract. A portion of the extract was filtered using a 0.45-μm micropore filter, and a full ICP elemental scan, including S, was conducted on the extract.

Lake water was analyzed for various properties as follows:

Ca, Mg, K, Na, Fe (total), Mn: APHA Method 3120
Bicarbonate, carbonate, hydroxide (as CaCO3), total alkalinity (as $CaCO_3$): APHA Method 2320
Chloride, nitrate-N, nitrite-N, sulphate: APHA Method 4110
Fluoride: APHA Method 4500F-c
Ammonia-N: APHA Method 500NH_3
Conductivity: APHA Method 2510
pH: APHA Method 4500H

Phosphorous (total): APHA Method 4500P-d
Turbidity: APHA Method 2130-b
Dissolved organic carbon: APHA Method 5310-b
Total hardness (as $CaCO_3$): APHA Method 2340-b
Total dissolved solids @ 105 °C: APHA Method 2540-c
Balance (sum cations/sum anions): APHA Method 1030-f

4.8 Meteorological Data

Precipitation data were obtained directly from the Atmospheric Environment Service, Environment Canada, for the years 1990 - 1995. This was supplemented by data from Canadian Climate Normals, 1961 - 1990 (Atmospheric Environment Service, Environment Canada 1993). Data were obtained for meteorological stations in the vicinity of the study area, at Coronation and Sibbald in Alberta, and Kindersley, Unity and Alsask in Saskatchewan. Information from the Esther station, which is within the study area, was characterized by data gaps and therefore was not used in the study. Precipitation amounts ranged from north to south within the study area. For modelling purposes, long-term annual averages of 400 mm yr^{-1} was applied to the north part of the study area, 376 mm in the middle part of the area, and 352 mm in the south part of the study area.

4.9 Precipitation Surplus

Some models use the term 'precipitation minus potential evapotranspiration' to obtain an approximation of the amount of deep percolation of soil moisture, or to approximate total precipitation surplus including runoff. Potential evapotranspiration exceeds precipitation in the study area, however, the depth of soil profile development suggests that water penetrates to about 0.8 metres in sandy soils in the study area. A soil depth of 25 cm was applied in determining acidification with models, this being the depth within which the majority of plant roots occur. Therefore, the amount of water percolating beyond the surface 25 cm zone was calculated.

Daily precipitation data for the months of April to October, inclusive, were obtained for the years 1990 to 1995. The amounts of precipitation retained by the soil on a daily basis was estimated by assuming a field capacity of 16.7 mm per 25 cm, this being based on an available water content of 80 mm per 1.2 metres for sandy soils in the study area (Tajek et al. 1989). The daily evapotranspiration rates were subtracted from this amount. Actual monthly evapotranspiration rates were obtained from Bothe and Abraham (1993). These rates were as follows: April, 2 mm d^{-1}; May, 4 mm d^{-1}; June, 6 mm d^{-1}; July, 7 mm d^{-1}; August, 6 mm d^{-1}; September, 4 mm d^{-1}; and, October, 2 mm d^{-1}. All winter snowfall was assumed to percolate into the soil, and evapotranspiration was assumed to be zero for this period.

The amount of percolation beyond the 25 cm zone varied widely among the five years. The average amounts calculated for the northern, central and southern parts of the study area were 107, 92 and 78 mm per year, respectively.

The difference between the precipitation and the precipitation surplus represents the proportion of the precipitation that reacts with the upper 25 cm soil layer. Another implication of the precipitation surplus concept is that the products of any reactions within the top 25 cm of the soil are carried down the profile; that is, base cations may be lost from the upper layer.

While most roots are assumed to occur in the top 25 cm, a proportion occurs at some depth in the profile and take up nutrients as well as water. Thus, it is possible that upward movement of nutrients through these deep roots would add nutrients to the upper soil layers, which would serve to counteract the effects of acidification on plants whose roots occur in the top 25 cm of the soil. However, it is difficult to estimate the amount of upward nutrient transport by deep roots. It is considered that this is a minor process within the ecosystem, and therefore, this amount was not estimated and it was assumed for modelling purposes that no nutrient return occurs by this mechanism.

4.10 Acid Deposition Data

Acid deposition data was obtained from province-wide estimates of deposition by Cheng et al. (1997). In the case of the ARC model, the Potential Acid Input (PAI) was applied. In the case of the SMART model, this was subdivided into sulphur, nitrogen and base cation components, as required for model input. Total nitrogen deposition was divided into the amounts of deposited NO_x and NH_x according to ratios reported for the Crossfield site in the Acid Deposition Research Program (Legge and Krupa (1990). These were approximated at 1/3 NO_x and 2/3 NH_x, in terms of keq ha^{-1} yr^{-1}.

Wet and dry deposition amounts were required for the Simple Mass Balance method of critical load determination. It was assumed that the ratio between the two was 1:1. Comparison of wet deposition chemistry obtained from the Esther monitoring station with the total PAI estimated by Cheng et al. (1997) suggests that this is a valid approximation of wet and dry deposition.

The PAI reported by Cheng et al. (1997) for the Provost-Esther grid cell was 0.15 to 0.20 keq H^+ ha^{-1} yr^{-1}. The upper number in this range (0.20 keq H^+ ha^{-1} yr^{-1}) was applied in models. This rate is equivalent to 0.3 keq H^+ ha^{-1} yr^{-1} of SO_x, NO_x and NH_x deposition, partially neutralized by 0.1 keq H^+ ha^{-1} yr^{-1} of base cation deposition.

4.11 Other Data Requirements

The dynamic models have a number of data inputs consisting of constants, coefficients, soil analytical data or soil parameters obtained from the literature. A number of these and their sources are listed below.

- ***Soil bulk density:*** from average bulk densities based on texture in Tajek et al. (1989)
- ***Thickness of the soil compartment:*** set at 0.25 m, unless otherwise indicated
- ***Volumetric H_2O:*** set at field capacity, as derived from regressions on texture in Tajek et al. (1989)
- ***Initial amount of carbonates:*** from laboratory analysis
- ***Organic matter content of topsoil:*** from laboratory analysis
- ***Initial C:N ratio in organic matter:*** from laboratory analysis
- ***log_{10} of selectivity constant for Al-BC exchange:*** default value is 1, unless otherwise indicated
- ***log_{10} of selectivity constant for H-BC exchange:*** value as defined in model (5.176 in SMART model)
- ***log_{10} of gibbsite equilibrium constant:*** value as defined in model (8.77 in SMART model)
- ***Initial exchangeable base saturation:*** from analytical data
- ***Nitrification factor:*** fraction of NHx nitrified, assumed to be 1 (100%)
- ***De-nitrification factor:*** assumed to be zero for well aerated soils
- ***Initial Al buffer capacity:*** derived from reported levels of Al oxyhydroxides in Alberta soils
- ***Maximum SO_4 adsorption capacity:*** assumed to be zero
- ***Concentration of organic acids:*** value of 0.1 $mol_c\ m^{-3}$ from literature on Alberta soils
- ***Parameters for pKa (organic acids):*** default values in models applied (0.96, 0.9 and 0.039 in SMART model)
- ***pCO_2 in soil solution:*** default values in models applied (63, as a multiple of pCO_2 in air (atm), in SMART; 0.005 atm partial pressure in ARC model)

4.12 Map Compilation

A soil map of the Provost-Esther study area was developed from the AGRASID soils database and PFRA land cover databases as described in Section 4.2. Only information at the Land System level was used, as this is an appropriate level of detail for depicting the distribution of soil types and their sensitivity to acid deposition. Additionally, it provided a suitable level of stratification for planning a soil sampling program.

Digital files for base map information as well as land use data were obtained from the PFRA-WGTPP data base (Section 4.3). The base map files were registered to UTM Zone 12, NAD '83 coordinates. This coordinate system was maintained throughout all digital processing and formed the basis for geographic referencing of the final map products.

Delineations of Land Systems from the AGRASID database were linked to the base information using ARC/VIEW. The data were exported to ARC/INFO for topological construction, attribute linkage and map product output, the latter including incorporation of a soil sensitivity legend.

5.0 OVERVIEW OF SOILS AND SURFACE WATERS IN THE STUDY AREA

5.1 Ecological Stratification

The most detailed level of mapping in the AGRASID database is the Soil Landscape unit. A Soil Landscape is a subdivision of a Land System that displays a consistent and recognizable pattern of distribution of soils and landscape elements (CAESA Soil Inventory Working Group 1998). As indicated in Section 4.1, the Soil Landscape mapping unit was considered as being too detailed for application in this project, and the Land System was applied instead.

A map of Land Systems in the study area is presented in the back pocket of this report. A legend describes characteristics of the Land Systems in terms of parent geologic materials, landscapes and soil types. The Land Systems are also described in Table 3, in which additional information pertaining to extent of wetlands and saline areas is presented.

5.2 Soil Classification

Soils of the Brown Chernozem and Solodized Solonetz Great Groups dominate the soils in the Mixed Grassland Ecoregion. These are soils that occur under sub- to semi-arid conditions and have brownish-coloured topsoil (A) horizons with relatively low organic matter content. They are associated with xerophytic and mesophytic grass and forb vegetation.

Soils in the Moist Mixed Grass Ecoregion and the southern part of the Parkland Ecoregion are characterized by Dark Brown Chernozems. Dark Brown Chernozems have higher organic matter contents and darker coloured topsoils than Brown Chernozems. Under native vegetation, these soils are associated with a cover of mesophytic grasses and forbs under semi-arid climatic conditions. Solodized Solonetz soils occur in places.

In both the Brown and Dark Brown Chernozem soil areas, various Gleysolic subgroups occur in depressions, lake margins and other poorly drained areas. Some soils having no profile development are associated with sandy materials in dune systems, and with recently deposited alluvium along streams. Saline soils also occur sporadically through the area. The extent of these within Land Systems has been estimated by Strong and Thompson (1995) and is indicated in Table 3 (Section 5.1).

Individual soil types within Soil Landscapes are identified at the Soil Series level of the Canadian System of Soil Classification (Soil Classification Working Group 1998). A soil series is a category (or level) in the Canadian system of soil classification. It is the basic unit of soil classification, and consists of soils that are essentially alike in all major profile characteristics except the surface texture. Naming of Soil Series is based on Alberta Soil Names, Generation 2 in the AGRASID soil

names file (CAESA Soil Inventory Working Group 1998). Soil series within the study area are listed in Table 4.

Table 3. Description of the Land Systems in the Provost-Esther Grid-Cell

Land System Map Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Series	Wetland Area (%)[1]	Saline Area (%)	General Description
01.3d.01 Sounding Valley	Brown	Bingville (Orthic Brown Chernozem) Ronalaine (Solonetzic Brown Chernozem)	Bullpound (Brown Solonetz) Dishpan (Rego Gleysol)	0.0	0.0	Undulating landscape with some floodplain. Brown Chernozems developed on moderately coarse textured glaciofluvial sediments and medium textured till. Minor Solonetz and Gleysols.
01.3d.02 Sedalia Plain	Brown	Hemaruka (Brown Solodized Solonetz) Halliday (Brown Solod)	Maleb (Orthic Brown Chernozem) Cecil (Solonetzic Brown Chernozem)	0.1	0.0	Undulating landscape with some hummocky. Brown Solonetz developed on moderately fine textured till. Minor Chernozems.
01.4d.02 Calendula Upland	Brown	Maleb (Orthic Brown Chernozem) Foremost (Orthic Brown Chernozem)	Hemaruka (Brown Solodized Solonetz) Ronalaine (Solonetzic Brown Chernozem)	0.0	0.0	Hummocky landscape. Brown Chernozems developed on moderately fine textured till. Minor Solonetz.
01.4d.18 Salt Lake Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Neutral (Rego Dark Brown Chernozem) Onnevue (Solonetzic Dark Brown Chernozem)	0.2	0.0	Hummocky landscape with some ridged. Dark Brown Chernozems developed on moderately fine textured till. Significant eroded soils.

Land System Map Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Series	Wetland Area (%)[1]	Saline Area (%)	General Description
01.4f.02 Sibbald Plain	Brown	Chin (Orthic Brown Chernozem)	Acadia Valley (Calcareous Brown Chernozem) Maleb (Orthic Brown Chernozem)	0.1	0.0	Undulating landscape with some hummocky. Brown Chernozems on medium textured glaciolacustrine sediments. Minor fine textured soils.
01.4f.03 Mere Plain	Brown	Bingville (Orthic Brown Chernozem) Pemukan (Orthic Brown Chernozem)	Cavendish (Orthic Brown Chernozem) Chin (Orthic Brown Chernozem)	0.0	0.0	Undulating landscape. Brown Chernozems developed on moderately coarse and gravelly, very coarse glaciofluvial sediments.
02.4a.04 Pacific Creek Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Flagstaff (Solonetzic Dark Brown Chernozem)	0.0	0.0	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till.
02.4a.05 Grassy Island Plain	Dark Brown	Wainwright (Orthic Dark Brown Chernozem)	Metisko (Orthic Dark Brown Chernozem) Gough Lake (Rego Gleysol)	0.0	0.0	Landscape is undulating with some level, closed basin and duned. Dark Brown Chernozems on very coarse textured fluvioeolian sediments. Minor Gleysols and fine textured soils.
02.4a.06 Loverna Plain	Dark Brown	Metisko (Orthic Dark Brown Chernozem) Wainwright (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem)	0.0	0.0	Undulating landscape with some duned and hummocky. Dark Brown Chernozems developed on coarse textured glaciofluvial and very coarse textured fluvioeolian sediments.
02.4a.08 Altario Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Kirriemuir (Orthic Dark Brown Chernozem) Altario (Rego Dark Brown Chernozem)	0.0	0.0	Hummocky landscape. Dark Brown Chernozems developed on moderately fine textured till. Significant eroded soils.

Land System Map Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Series	Wetland Area (%)[1]	Saline Area (%)	General Description
05.2a.01 St. Lawrence Hills	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Gleysols Provost (Orthic Dark Brown Chernozem)	0.6	0.0	Undulating landscape with some hummocky and ridged. Dark Brown Chernozems on moderately fine textured till. Minor Gleysols.
05.2a.02 Gillespie Lowland	Dark Brown	Metisko (Orthic Dark Brown Chernozem) Dolcy (Orthic Dark Brown Chernozem)	Wainwright (Orthic Dark Brown Chernozem) Gleysols	7.0	0.0	Undulating landscape with some confined floodplain and numerous water bodies. Dark Brown Chernozems on moderately coarse glaciofluvial sediments and coarse glaciofluvial materials over moderately fine textured till. Minor Gleysols.
05.2a.03 Black Creek Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Provost (Orthic Dark Brown Chernozem) Gleysols	0.3	0.0	Hummocky landscape. Dark Brown Chernozems developed on moderately fine textured till. Minor Gleysols.
05.2a.04 Falcon Plain	Dark Brown	Hughenden (Orthic Dark Brown Chernozem) Provost (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem) Solonetzic soils	0.0	0.0	Hummocky landscape with some undulating. Dark Brown Chernozems developed on moderately fine textured till and medium textured material over moderately fine textured till. Minor Solonetz.

Land System Map Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Series	Wetland Area (%)[1]	Saline Area (%)	General Description
05.2a.07 Hansman Plain	Dark Brown	Coronation (Orthic Dark Brown Chernozem) Provost (Orthic Dark Brown Chernozem)	Metisko (Orthic Dark Brown Chernozem) Solonetzic soils	0.9	0.0	Undulating landscape with some hummocky. Dark Brown Chernozems developed on medium textured glaciofluvial sediments and medium textured materials over moderately fine textured till. Minor Solonetz and coarse textured soils.
05.2b.07 Sunken Lake Plain	Dark Brown	Wainwright (Orthic Dark Brown Chernozem) Metisko (Orthic Dark Brown Chernozem) Houcher (Rego Dark Brown Chernozem)	Dolcy (Orthic Dark Brown Chernozem) Gleysols	1.8	0.0	Duned landscape with some undulating. Dark Brown Chernozems developed on very coarse to coarse textured glaciofluvial and fluvioeolian sediments. Minor Gleysols. Significant eroded soils.
05.2b.09 David Lake Plain	Dark Brown	Metisko (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem) Monitor (Rego Dark Brown Chernozem)	1.7	0.0	Undulating landscape. Dark Brown Chernozems on moderately coarse textured glaciofluvial sediments. Significant eroded soils.

1 - Wetland area excludes lakes

Table 4. Soil Series within the Provost-Esther Grid Cell

Symbol	Series	Classification	Drainage	Parent Material	Parent Material Texture
ACV	Acadia Valley	Calcareous Brown Chernozem	Well	Glaciolacustrine	Very fine
ALT	Altario	Rego Dark Brown Chernozem	Well	Till	Medium
BLP	Bullpound	Brown Solonetz	Mod Well	Glaciolacustrine	Moderately fine
BVL	Bingville	Orthic Brown Chernozem	Rapid	Glaciofluvial	Moderately coarse
CCL	Cecil	Solonetzic Brown Chernozem	Well	Till	Moderately fine
CHN	Chin	Orthic Brown Chernozem	Well	Glaciolacustrine	Medium
CNN	Coronation	Orthic Dark Brown Chernozem	Well	Glaciolacustrine	Medium
CVD	Cavendish	Orthic Brown Chernozem	Rapid	Fluvioeolian	Very coarse
DCY	Dolcy	Orthic Dark Brown Chernozem	Mod Well	Glaciofluvial/till	Moderately coarse/ moderately fine
DHP	Dishpan	Rego Gleysol	Poorly	Lacustrine	Moderately fine
FMT	Foremost	Orthic Brown Chernozem	Well	Till	Medium
FST	Flagstaff	Solonetzic Dark Brown Chernozem	Well	Till	Moderately fine
GLK	Gough lake	Rego Gleysol	Poorly	Glaciolacustrine	Fine
HCH	Houcher	Rego Dark Brown Chernozem	Rapid	Fluvioeolian	Very coarse
HDY	Halliday	Brown Solod	Well	Till	Moderately fine
HKR	Halkirk	Dark Brown Solodized Solonetz	Well	Till	Moderately fine
HND	Hughenden	Orthic Dark Brown Chernozem	Well	Till	Moderately fine
HUK	Hemaruka	Brown Solodized Solonetz	Well	Till	Moderately fine
KUR	Kirriemuir	Orthic Dark Brown Chernozem	Well	Till	Medium
LTH	Leithead	Dark Brown Solodized Solonetz	Rapid	Glaciofluvial	Moderately coarse
MAB	Maleb	Orthic Brown Chernozem	Well	Till	Moderately fine
MET	Metisko	Orthic Dark Brown Chernozem	Rapid	Glaciofluvial	Moderately coarse
MTR	Monitor	Rego Dark Brown Chernozem	Well	Glaciolacustrine	Medium
NUT	Neutral	Rego Dark Brown Chernozem	Well	Till	Moderately fine

Symbol	Series	Classification	Drainage	Parent Material	Parent Material Texture
OVE	Onnevue	Solonetzic Dark Brown Chernozem	Mod Well	Till	Moderately fine
PRO	Provost	Orthic Dark Brown Chernozem	Well	Glaciolacustrine /till	Medium/ moderately fine
PUN	Pemukan	Orthic Brown Chernozem	Well	Glaciofluvial	Very gravelly, very coarse
ROL	Ronalaine	Solonetzic Brown Chernozem	Well	Till	Moderately fine
VST	Vendisant	Rego Brown Chernozem	Rapid	Fluvioeolian	Very coarse
WWT	Wainwright	Orthic Dark Brown Chernozem	Rapid	Fluvioeolian	Very coarse

Source: AGRASID Database (CAESA Soil Inventory Working Group 1998)

5.3 Soil and Land Cover Map

Soil types, land use and distribution of surface water bodies are shown on the map 'Land Systems, Land Cover and Soil Sensitivity to Acid Inputs in the Provost-Esther Grid Cell' (back pocket). The surficial materials consist mainly of glacial till, glaciofluvial and fluvioeolian deposits. ('Fluvioeolian' refers to a complex of glaciofluvial deposits with eolian deposits occurring as blankets and dunes.) Landscapes range from undulating to hummocky. A legend accompanying the map indicates the dominant and minor soil series within each Land System, along with the parent materials and landscape features.

Land cover in the study area was categorized as cultivated, grassland, shrubland or treed land. The distribution and extent of these land cover types is indicated in the Land System map (back pocket). Land systems characterized by sandy soils have extensive areas of grassland. The Land Systems in the northern part of the area are also dotted with various sized areas of shrublands. Very few small areas of treed lands were mapped in the area. However, it was noted during the field survey that areas mapped as shrublands were in fact under aspen cover. In the southern part of the area, the extent of shrublands is considerably less, and these are in most places characterized by very scrubby aspen associated with willows, wolf willow and other shrubs.

Grasslands are also characteristic of some Land Systems characterized by glacial till surficial deposits. These areas have hummocky terrain with moderate to steep slopes that limit suitability for tillage agriculture, and they are consequently used mainly as rangeland.

5.4 Description of Sampled Soils

Locations and descriptions of soils sampled in the study area are presented in Appendix A. Analytical data for the soils are presented in Appendix B.

5.4.1 Landscape Influences on Soils

Soil samples were collected in upper and lower landscape positions at five sites characterized by roughly undulating to hummocky topography with moderate slopes. All other sites occurred on gently undulating landscapes. Chemical properties of the soils in different landscape positions were compared in order to determine if there might be differences in sensitivity to acidic inputs, and to determine if slope position has a large enough influence such that the land area with assigned critical loads would need to be adjusted. Properties of these soils are presented in the Appendices. Some observations are as follows:

Site 1 (upper slope) and Site 2 (lower slope): Upper slope pH was slightly higher than the lower slope pH in the Ah horizon (pHw 6.1 vs. 5.7), and the upper slope pH in the Bm horizon is almost a unit higher (pHw 6.6 vs. 5.7). CEC values were similar.

Site 5 (upper slope) and Site 6 (lower slope): pH was somewhat lower in the Ah horizon of the upper slope soil (pHw 6.3 vs. 7.6), and that in the Bm horizon was much lower (pHw 6.1 vs. 8.4). The high pH in the lower slope position indicates salinity.

Site 14a (upper slope) and Site 14b (lower slope): pH was similar in all equivalent layers in both landscape positions. This site was treed, with relatively steeply sloping topography as compared to other sites.

Site 16a (upper slope) and Site 16b (lower slope): pH was similar in both landscape positions (upper slope pHw 6.2 vs. lower slope pHw 5.7 in the Ah horizon, and upper slope pHw 7.9 vs. lower slope pHw 7.5 in the B horizon). However, profile morphology differed. The upper slope soil was slightly saline (Wainwright series) while the lower slope soil was Solonetzic (Leithead series).

Site 26 (upper slope) and Site 26a (lower slope): pH was slightly lower in the Ah horizon of the upper slope soil (pHw 5.8 vs. 6.3), as well as in the Bm horizon (pHw 6.2 vs. 6.5).

The Site 5/6 and Site 16a/16b landscape pairs occur near low lying areas, one of which was a nearly dry slough. Wetlands in the study area are characterized by salinity; therefore, soils in lower slope positions represent a transition from saline wetlands to nonsaline upland soils. It is estimated that these transitional areas account for a small proportion (<10%) of the total landscape, and therefore should not greatly affect estimates of soil areas with different critical loads.

The Site 1/Site 2 pair represents a difference between an upper slope grassland soil and a lower slope treed soil. The lower slope soil could be relatively more sensitive to acid deposition due to its lower pH.

The other two landscape pairs (14a/14b and 26/26a) showed little difference in pH between upper and lower slope positions. Sites 14a and 14b were both under treed (aspen) vegetation, while Sites 26 and 26a were under grassland. The low areas were not poorly drained, but were well drained depressions among sand dunes.

The information about soil types in differing landscape positions is captured to an extent through the soil series composition of Land Systems. For example, Gleysolic (poorly drained) soils are indicated as a minor component of the Sunken Lake Plain (Table 3). Lower slope soils with salinity and/or high pH would be partly included in this component. The quantitative estimate of soils indicated as being 'minor' in the landscape is about 10%, although this may vary by about 50 percent.

Wooded landscapes are especially prevalent in the Sunken Lake Plain. The Site 1/2 and Site 14a/14b pairs both occur in this Land System. One site had little difference in pH between the upper and lower landscape positions, while the other had higher acidity in the lower slope position. In hummocky terrain, it is estimated that the lower slope positions occupy about 10 percent of the landscape.

It is concluded that estimates of land areas having different critical loads arising from soil properties differing due to landscape position could be in error by about 10 percent. Estimates such as these are based on soil survey information which were originally made by visual estimation. As noted above, the error associated with such estimates can be quite high, being in the order of 50 percent, and possibly as high as 100 percent in some cases.

5.5 Surface Waters

The largest water bodies in the area are Grassy Island Lake, Sounding Lake, Fleeinghorse Lake, Hansman Lake, St. Lawrence Lake, Gillespie Lake and Dragon Lake. Numerous other small lakes, some of which are named, occur throughout the area. Almost all lakes were dry or very shallow at the time of field investigations in late fall, 1999. The dry lake beds were characterized by white salt encrustations, as were the margins of lakes containing water. Some lakes that appeared to be deeper than most occur in and around Sec. 5 - Tp. 31 - R. 1 - W3, in the southeast of the area. Fleeinghorse Lake, adjacent to the town of Provost, also appeared to be relatively deep.

Wetlands in the area occur as small poorly drained depressions and as more extensive areas associated with lakes. The extent of wetlands in each of the Land Systems, derived from information provided in Strong and Thompson (1995), is presented in Table 3 (Section 5.1).

Water chemistry data for lakes within the study area are not available. Data for some lakes near the study area are given in Table 5. Two of the lakes are characterized by high TDS and alkalinity. The others have lower values for these parameters, but all are nevertheless rated as Low in acidification sensitivity using the criteria of Saffran and Trew (1996).

The one lake sampled within the study area (Table 5) is likewise characterized by high alkalinity, TDS, pH and Ca content. The water chemistry of this and neighbouring lakes, coupled with observations of visible salinity associated with lakes, indicate that surface waters in the Provost-Esther area have Low sensitivity to acidifying inputs, and it was concluded that derivation of critical loads for surface waters in the study area is not warranted.

Table 5. Water Chemistry of Lakes Within and In the Vicinity of the Provost-Esther Study Area

Lake	Location	pH	Ca (mg L^{-1})	Alkalinity (mg L^{-1} $CaCO_3$)	TDS (mg L^{-1})	Acidification Sensitivity
Shornecliffe	25-40-7-4	9.2	13	702	2,240	Low
Gooseberry	26-36-6-4	9.8	12	6,593	44,638	Low
Goose	34-31-10-4	8.3	35	149	155	Low
Dillberry	36-41-1-4	8.6	22	193	188	Low
SE5-31-1-4[1]	SE5-31-1-4	8.9	40	1,555	60,400	Low

1 - Lake sampled in the study area

6.0 CRITICAL LOAD DETERMINATIONS FOR SOILS

6.1 Empirical Method

The empirical method as adapted in the UK from the Skokloster approach (Section 2.3) was applied to soils in the Provost-Esther study area. The application of this approach begins with allocation of a soil to a particular sensitivity and critical load class (Table 6). This scheme places clay minerals in the second class. However, the exchange capacity and exchangeable cations carried by clay minerals are not taken into account, and placing a clayey soil into Class 2 was not considered as being appropriate (Hornung et al. 1995). Therefore, a particle size classification was developed for modifying the initial mineralogically-based classes (Table 7). In addition to the soil textural modifiers, various other factors were considered in determining the final classification ratings for different soil types (Table 8). As an example, a soil overlying quartzite bedrock would be allocated to Class 1 in the Skokloster classification system. However, if the soil was poorly drained and loamy-sand in texture, it would be allocated to Class 2, with a higher critical load. Similarly, if the soil was a deep sand, it would also be allocated to Class 2.

Table 6. Mineralogical Classification and Critical Loads for Soils (0-0.5 m) According to the Skokloster Classification [1]

Class	Dominant Weatherable Minerals	Critical Load (keq H^+ ha^{-1} yr^{-1})
1	Quartz, rutile, anatase, kaolinite, gibbsite, orthoclase	< 0.2
2	Muscovite, plagioclase, illite, montmorillonite, vermiculite	0.2 – 0.5
3	Amphibole, chlorite, biotite, epidote, glaucophane	0.5 – 1.0
4	Olivine, garnets, pyroxenes, epidote	1.0 – 2.0
5	Carbonates	> 2.0

1 - After Nilsson and Grenfeldt (1988) and Sverdrup and Warfvinge (1988)

Table 7. Allocation to Skokloster Material Class Based on Particle Size Class[1]

Particle size class	Soil material class
Sand, loamy sand, sandy loam, (sandy) silt loam	Class 2
Clay loam, sandy clay loam, silt loam	Class 3
Clay, silty clay, sandy clay	Class 4

1 - After Hornung et al. (1995)

Table 8. Factors Causing a Decrease or Increase in Critical Loads of Acidity for Soils[1]

Factor	Decrease	Increase
Precipitation	High	Low
Vegetation	Coniferous forest	Deciduous forest
Elevation slope	High	Low
Soil texture	See Table 7	See Table 7
Soil drainage	Free	Impeded
Soil/till depth	Shallow	Thick
Sulphate adsorption capacity	Low	High
Base cation deposition	Low	High

1 -After Nilsson and Grenfeldt (1988) and Hornung et al. (1995)

The combination of mineralogical and particle size classes of sand to sandy loam soils in the study area would result in allocation to a critical load category of 0.2-0.5 keq ha^{-1} yr^{-1} (class 2). In the UK approach, the critical load is either increased or decreased, depending on various modifying factors, as indicated above. The factors of low precipitation, low elevation, and thick soil would increase the critical load. However, the factors of free drainage and low sulphate adsorption capacity serve to reduce the critical load. The base cation deposition rate is another modifying factor; the level in the study area, however, is of intermediate magnitude (Cheng et al. 1997) and therefore has little impact on the overall rating. The factors more or less balance each other, and we therefore deduce that very sandy soils (sand, loamy sand) likely have a critical load in the range of 0.2 - 0.5 keq ha^{-1} yr^{-1}. This would apply particularly to soils with low organic matter content. The classification for sandy loam soils is likely in the upper part of the range, and possibly in the 0.5-1.0 keq ha^{-1} yr^{-1} range. Allocation of soil units using this empirical method leads to the assignment of critical loads in the Provost-Esther study area as presented in Table 9.

Table 9. Critical Loads of Soils in the Provost-Esther Area Based on the Empirical Method

Texture	Soil Series	Critical Load
Very coarse	Wainwright, Cavendish	0.2-0.5 keq ha^{-1} yr^{-1}
Moderately coarse	Metisko, Bingville	0.5-1.0 keq ha^{-1} yr^{-1}
Medium to moderately fine	Series on till	1.0-2.0 keq ha^{-1} yr^{-1}
Fine	Glaciolacustrine clays	>2.0 keq ha^{-1} yr^{-1}

6.2 Steady State Mass Balance Method

6.2.1 *Model Description*

The Steady State Mass Balance Method considers the soil as consisting of one compartment equal to the thickness of the root zone (generally 30-50 cm in forest soils) and critical chemical values relate to element concentrations leaching from the root zone. The calculation of critical loads using the Steady State Mass Balance (SMB) model is based on a balance of sources of acidity against sinks for acidity and sources of alkalinity, and starts with a formulation of the charge balance of ions in the soil leachate flux (Sverdrup and de Vries 1996; de Vries 1991), as follows:

$$H_{le} + Al_{le} + BC_{le} + NH_{4,le} = SO_{4,le} + NO_{3,le} + Cl_{le} + HCO_{3,le} + RCOO_{le} \quad (6)$$

where le refers to leaching out of the rooting zone, BC is the sum of base cations (Ca +Mg + K + Na), RCOO is the sum of organic anions, and Al is the sum of all positively charged aluminum species. The concentrations of OH and CO_3 are assumed to be zero. The leaching of Acid Neutralizing Capacity (ANC) is defined as:

$$ANC_{le} = HCO_{3,le} + RCOO_{le} - H_{le} - Al_{le} \quad (7)$$

Combining equations (6) and (7) yields:

$$BC_{le} + NH_{4,le} - SO_{4,le} - NO_{3,le} - Cl_{le} = ANC_{le} \quad (8)$$

There are no sources or sinks of chloride in soil, and chloride leaching is therefore considered as being equal to chloride deposition.

The leaching of cations is balanced by a net input of base cations in a steady-state situation, and the following relationship holds:

$$BC_{le} = BC_d + BC_w - BC_u \quad (9)$$

where the subscripts d, w and u stand for deposition, weathering and net vegetation growth uptake, respectively. Base cation input by litterfall and base cation removal in leaves is not considered since the fluxes are assumed to be equal in a steady-state situation. The balance at steady-state also implies that there is a constant pool of exchangeable base cations and therefore base saturation percentage does not change over time. In reality, exchangeable base cations might buffer incoming acidity for decades, but this is considered as a temporary effect and cannot be taken into account under long-term, steady-state conditions.

The leaching of sulphate and be linked to its deposition by mass balance for S (de Vries 1991):

$$S_{le} = S_d - S_{ad} - S_u - S_i - S_{re} - S_{pr} \quad (10)$$

The subscripts refer to; ad - adsorption, i - immobilization, re - reduction and pr - precipitation. These terms are considered to be either insignificant or at steady in soils, and are therefore not considered. Since sulphur is completely oxidized in the soil profile, $SO_{4,le} = S_d$, yielding:

$$S_{le} = S_d \quad (11)$$

Similar considerations with respect to nitrogen lead to the following relationship (Sverdrup and de Vries 1996; de Vries 1991):

$$N_{le} = NO_{3,le} = N_d - N_i - N_u - N_{de} \quad (12)$$

where d is deposition, i is immobilization, u is vegetation uptake and de is denitrification .

The combination of equations for S and N leads to a simplified acidity balance in the soil:

$$S_d + N_d - BC_d + Cl_d = BC_w - BC_u + N_i + N_u + N_{de} - ANC_{le} \quad (13)$$

A critical load of potential acidity is defined by specifying a critical ANC_{le}, which is a criterion linking chemical changes in soil to potential harmful effects:

$$CL(Ac_{pot}) = BC_w - BC_u + N_i + N_u + N_{de} - ANC_{le(crit)} \quad (14)$$

Distinction is made between 'land use acidity' ($N_i + N_u + N_{de} - BC_u$) and 'soil acidity' ($BC_w - ANC_{le(crit)}$). A critical load that is an intrinsic ecosystem property that will not change over time requires neglecting of land use terms, as these are changeable. Hence, the critical load is defined as the critical load of "actual acidity" (Sverdrup and de Vries 1994), as follows:

$$CL(Ac_{act}) = BC_w - ANC_{le(crit)} \quad (15)$$

Critical ANC leaching ($ANC_{le(crit)}$) can be defined in terms of soil acidity as follows:

$$ANC_{le(crit)} = -Alle_{(crit)} - H_{le(crit)} = -Q \bullet ([Al]_{crit} + [H]_{crit}) \quad (16)$$

Q is the precipitation surplus, or water leaving the root zone ($m^3\ ha^{-1}\ yr^{-1}$), and the square brackets denote concentrations (in eq m^{-3}).

The relationship between Al and H is defined by a gibbsite equilibrium:

$$[Al] = K_{gibb} \bullet [H]^3 \text{ or } [H] = ([Al]/K_{gibb})^{1/3} \quad (17)$$

A critical ANC leaching term ($ANC_{le(crit)}$) can be obtained by specifying a critical Al concentration or a critical pH. However, the most widely used critical threshold related to soil toxicity is the base cation to Al ratio in soil solution. The term used for base cations is Bc, which is different from BC used previously because Na is excluded from the summation; i.e., Bc = Ca + Mg + K. Sodium (Na) is excluded as it does not provide protection against Al for plants. The critical Al leaching is related to leaching of base cations (Bc_{le}) and the critical Bc:Al ratio in soil solution:

$$Alle_{(crit)} = 1.5 \bullet Bc_{le}/(Bc:Al)_{crit} \quad (18)$$

The factor 1.5 arises from the conversion of mols to equivalents. The Bc_{le} term is derived from the mass balance for base cations (equation 9 above).
The incorporation of these relationships in the CL expression (equation 15) provides the SMB equation for critical load of acidity in eq ha^{-1} yr^{-1}, as follows (Sverdrup and de Vries 1994):

$$CL = BC_d - Cl_d + BC_w - BC_u + 1.5 \bullet \{Bc_d + Bc_w - Bc_u)/(Bc/Al)_{crit}\} \quad (19)$$

$$+ Q^{2/3} \bullet \{1.5 \bullet (Bc_d + Bc_w - Bc_u)/((Bc/Al)_{crit} \bullet Kgibb)\}^{1/3} \quad (20)$$

In this formulation, $Bc_w = 0.7\ BC_w$. , where BCw the sum of Ca, Mg, K and Na from weathering. The factor 0.7 is applied to the total weathering to account for the inability of plants to use Na. The expression as presented by Sverdrup and de Vries (1994) is:

$$CL = BC_w + \{1.5 \bullet (0.7\ BC_w + Bc_d + Bc_u)/((Bc:Al)_{crit} \bullet Kgibb)\}^{1/3} \bullet Q^{2/3}$$
$$+ 1.5 \bullet (0.7\ BC_w + BC_d + BC_u)/(Bc:Al)_{crit}) \quad (21)$$

The Task Force on Mapping (1996) referred to CL as $Cl_{max}(S)$, the maximum critical load of sulphur. This expression is also termed the critical load of acidity for situations where only sulphur is of concern, or if the CL is to be related to sulphur management strategies. If a portion of acidity is due to N and H, then this proportion is multiplied by the 'sulphur fraction', or that fraction of total acidity due to sulphur deposition, in order to obtain the maximum critical load of S. In deriving critical loads for the Provost-Esther study area, however, equation (21) is applied and the CL applies to the total acid input.

6.2.2 Data for Critical Load Calculations

Precipitation Surplus (Q)

Q is calculated as the precipitation minus the sum of interception evaporation by a forest canopy, the actual soil evaporation and the actual transpiration (water uptake) in the root zone. The precipitation surplus term was discussed in Section 4.8. The estimate in units entered into the SMB calculation are 690 m^3 ha^{-1} yr^{-1} for the northern (Provost) part of the area, 600 m^3 ha^{-1} yr^{-1} for the central part of the study area, and 500 m^3 ha^{-1} yr^{-1} for the southern (Esther) part of the area.

Gibbsite Equilibrium Constant (K_{gibb})

The value of K_{gibb} depends on soil type and the organic matter content. A widely used default value is K_{gibb} = 300 m^6 eq^{-2}, and other values are presented by the Task Force on Mapping (1996). The default value was applied in calculations for soils in the study area.

Weathering Rates (BCw)

A number of options for estimating weathering rates were presented by the Task Force on Mapping (1996), and are described in greatest detail by Sverdrup and de Vries (1994) and Sverdrup (1990). Wherever detailed soil mineralogical data is available, the PROFILE model (Sverdrup 1988) can be applied to determine weathering rates.

Methods for weathering estimation presented by Sverdrup (1990) include the 'base mineral index correlation' and the 'soil base cation content correlation'. The base mineral index correlation requires estimates of heavy mineral (minerals of specific gravity >2.70) content in soils. Application of these methods to data presented by Sverdrup (1990) for sandy soils suggests that the weathering rate is in the range of 0.05 to 0.4 keq ha^{-1} yr^{-1} for a 1 metre soil layer, or about 0.01 to 0.1 keq ha^{-1} yr^{-1} for a 0.25 metre layer. A value of 0.07 keq ha^{-1} yr^{-1} for a 0.25 m layer has been determined for sandy soils in Minnesota by Bloom and Grigal (1985), and was subsequently considered as a suitable approximation for sandy soils in Alberta by Abboud and Turchenek (1990) and Turchenek et al. (1994). This rate was therefore applied to soils in the Provost-Esther grid cell.

Critical loads were determined for a 0.5 m soil thickness as well as for a 0.25 m thickness. In the case of soils with sand to loamy sand textures, the weathering rate of 0.07 keq ha^{-1} yr^{-1} was applied to the 0.25 m scenario, and 0.14 keq ha^{-1} yr^{-1} to the 0.5 m scenario. Some soils in the area that were preliminarily allocated to a Moderate acidification sensitivity class (Section 4.2) have loamy sand to sandy loam textures. These soils likely have higher weathering rates than sandy soils; these were estimated by doubling the rates for very sandy soils, such that 0.14 keq ha^{-1} yr^{-1} was applied to the 0.25 m scenario, and 0.28 keq ha^{-1} yr^{-1} to the 0.5 m scenario.

Growth Uptake or Export of Base Cations (Bc_w)

Over a long-term, the net uptake of base cations (Bc; Ca, Mg and K, with Na excluded) is equal to removal in harvested biomass. In the case of forest biomass, the content of base cations in

harvestable timber is determined by elemental analysis of wood and estimation of wood mass. In the case of grasslands, annual growth (biomass) is returned to the soil each year, and storage of cations in biomass was considered for modelling purposes to be negligible as compared to forests.

The native grassland systems in the Provost-Esther study area can be regarded as extensive livestock farming systems, which are described as systems based on grazing (pastoral) and with little or no fertilizer usage and supplemental feeding (Frissel 1978). A provisional model of soil acidification developed for New Zealand pastoral systems considers acidification as being due to (1) soil organic matter accumulation, (2) nutrient transfer and removal by animals, (3) nitrate leaching as a consequence of ingested N return to soil by animals, and (4) fertilizer induced acidification (de Klein et al. 1997). Soil organic matter (SOM) accumulation and nutrient transfer/removal can be regarded in the same way as removal by harvested biomass; that is, the acidification factor is equivalent to the amount of base cations either removed or fixed in biomass. In the absence of actual data, it is assumed that the SOM contents of the sandy grassland soils in the Provost-Esther study area are likely at or close to a steady-state, the accumulation of SOM occurring at more or less the same rate as SOM mineralization. The main nutrient removal or fixing mechanism, therefore, is that due to animals.

Little data is available for nutrient removal rates from rangelands by animals. Heady and Child (1994) reported exports of 0.025 to 0.035 keq ha^{-1} yr^{-1} of base cations from rangelands in New Mexico. These data suggest that export of nutrients by beef production is low, and rates for northern climates on poor soils would likely be even lower, due to lower stocking rates. Therefore, base cation export by animals was considered as negligible in deriving critical loads by the SMB or other methods, and was therefore set to zero in the model runs.

Some of the study area has a cover of aspen and growth uptake of base cations may be significant as compared to grassland uptake and export. A study of ecosystems in the Wainwright sand dune area, which is close to the study area, indicated that trees were up to 7 m tall and about 45 years old. Base cation content was estimated by equating aspen stands in the area to a very low site index and applying chemical composition data for aspen trees from a Forestry Canada study of stands in New Brunswick (Maliondo et al. 1990), resulting in an Bc uptake term of 0.1 keq ha^{-1} yr^{-1}.

Base Cation Deposition (D)

Base cation deposition was estimated at 0.1 keq ha^{-1} yr^{-1} on the basis of data in Cheng et al. (1997) (Section4.9).

BC:Al Ratio

Base cation to aluminum ratios used in the calculations were 1, 10, 45 and 250 (Section 2.2.3).

6.2.3 *Critical Load Calculations*

Critical loads were calculated using the SMB model (equation 21) for 0.25 and 0.5 m soil layers. Critical load calculation by the SMB method was not conducted on the basis of properties of the soil samples collected, but rather on the basis of weathering rates of two broad soil groupings (sand to loamy sand, and loamy sand to sandy loam soils), on regional variation in climate expressed as variation in precipitation surplus, and on differences in growth uptake of base cations by differing vegetative cover. As indicated above, grassland sites were assumed to have negligible base cation export, while aspen woodland, which occurs mostly in the central part of the area, was considered to have a depletion rate of 0.1 keq ha^{-1} yr^{-1}.

The results of SMB calculations (Table 10) showed that critical loads at the BC:Al ratio of 1 are two to three times greater than those at BC:Al ratios of 10 or greater. (Note: The expression 'BC' is used heretofore, although it is equivalent to 'Bc' defined above.) However, increasing the BC:Al ratio beyond 10 reduced the critical load only slightly. The critical load calculations by the SMB method based on the recommended critical chemical value of 45 for the BC:Al ratio (Section 2.2.5) are presented in Table 11. The lowest critical loads were obtained for the sandy to loamy sand soils with aspen cover. When the soil was considered as a 0.25 metre layer, critical loads were relatively low while critical loads calculated for a 0.5 metre layer were somewhat higher due the additional weathering afforded by the larger soil mass.

Table 10. Critical Load Calculations by the SMB Method

Soil Texture	Depth (m)	BC:Al Ratio	Central Aspen CL (keq ha^{-1} yr^{-1})	North Grassland CL (keq ha^{-1} yr^{-1})	Central Grassland CL (keq ha^{-1} yr^{-1})	South Grassland CL(keq ha^{-1} yr^{-1})
S-LS	0.25	1	0.21	0.35	0.34	0.33
S-LS	0.25	10	0.11	0.13	0.13	0.12
S-LS	0.25	45	0.09	0.10	0.10	0.09
S-LS	0.25	250	0.08	0.08	0.08	0.08
S-LS	0.5	1	0.35	0.47	0.47	0.46
S-LS	0.5	10	0.18	0.20	0.20	0.19
S-LS	0.5	45	0.16	0.17	0.16	0.16
S-LS	0.5	250	0.15	0.15	0.15	0.15
LS-SL	0.25	1	0.37	0.50	0.49	0.48
LS-SL	0.25	10	0.19	0.21	0.21	0.20
LS-SL	0.25	45	0.17	0.17	0.17	0.17
LS-SL	0.25	250	0.15	0.16	0.16	0.15
LS-SL	0.5	1	0.65	0.77	0.77	0.76
LS-SL	0.5	10	0.35	0.36	0.36	0.35
LS-SL	0.5	45	0.31	0.31	0.31	0.31
LS-SL	0.5	250	0.29	0.30	0.29	0.29

Table 11. Summary of Critical Load Calculations by the SMB Method

Location	Cover	Critical Load, 0.25 m (keq H^+ ha^{-1} yr^{-1})	Critical Load, 0.5 m (keq H^+ ha^{-1} yr^{-1})
Central Area	Aspen on Sand to Loamy Sand	0.09	0.16
Northern Area	Grassland on Sand to Loamy Sand	0.10	0.17
Central Area	Grassland on Sand to Loamy Sand	0.10	0.16
Southern Area	Grassland on Sand to Loamy Sand	0.09	0.16
Northern Area	Grassland on Loamy Sand to Sandy Loam	0.17	0.31
Central Area	Grassland on Loamy Sand to Sandy Loam	0.17	0.31
Southern Area	Grassland on Loamy Sand to Sandy Loam	0.17	0.31

6.3 ARC Model

The ARC model (Turchenek and Abboud 1988) simulates soil chemical processes directly related to acidity and acidification of soils, and predicts the associated soil properties of pH, base saturation and solution Al3+ concentration. The ARC model is described in detail in Turchenek and Abboud (1988) and Abboud and Turchenek (1990). This model is adapted from the Bloom and Grigal (1985) model, with modifications for calculations of acid inputs and acidification processes, method of output of model results, and inclusion of calculations for base cation to aluminum (BC:Al) ratio. These are described in greater detail in the following sections.

6.3.1 Data for Critical Load Determinations

Soil Data Inputs

Soil data inputs for the ARC model were as follows:

- pH – by the $CaCl_2$ method;
- Cation exchange capacity and exchangeable bases – by the ammonium acetate extraction method;
- Partial pressure of CO_2 – 0.005 atmosphere;
- Activity coefficients of Al^{3+} and $Al(OH)^{2+}$ – 0.82 and 0.92, respectively (Bloom and Grigal 1985); and
- Weathering rate - 0.07 keq ha^{-1} yr^{-1}.

The input data for soil pH, CEC, and sum of bases were weighted mean values for the top 25 cm of air-dried mineral oil. The thickness of the soil horizons and the bulk density were considered in computing the means. The calculations were made as previously documented by Turchenek and Abboud (1988) and Abboud and Turchenek (1990).

Acid Deposition Data

Values for Potential Acid Input (PAI) as calculated by Cheng et al. (1997) were applied to determination of the possible acidification rates under current deposition conditions (Section 4.10). The PAI calculation accounts for both wet and dry forms of acid deposition. In order to determine critical loads, application of the model using a range of PAI values is necessary. The loads used in this modelling exercise were 0.5 keq ha^{-1} yr^{-1} and 1.0 keq ha^{-1} yr^{-1}, in addition to the estimate of current deposition at 0.2 keq ha^{-1} yr^{-1} (Section 4.10).

Climate Data

Data for precipitation and precipitation surplus as described in Sections 4.8 and 4.9 were applied in the model. Previous applications of the model used a 'precipitation minus potential evapotranspiration' term to determine the amount of precipitation water that percolates beyond the 0.25 cm layer. This calculation results in a negative value for climates characteristic of central and southern Alberta. The precipitation surplus concept (Section 4.9) provides a more realistic approximation of the amount of water that is actually evaporated or transpired by accounting for episodes of high precipitation and deep moisture percolation.

Time

The model can be executed for any specified length of time, and simulation results can be reported for any specified increment of time within the total simulation period. Predictive soil effects data are of greatest interest in terms of the immediate and near future; i.e., the period during which pollutant emissions can be forecast. It is also of interest, from a soil development point of view, to determine soil responses to acid deposition over very long periods of time since changes in soils occur slowly. Three hundred years was selected for the simulation period. This time frame would not obscure the data for interpretation of short-term effects, yet would provide a longer term view of soil changes.

Twenty years was selected as the increment of time between reported values in the simulations. This increment assured that sufficient data points were obtained for determining the trends of pH, base saturation, Al^{3+} levels and BC:Al ratios over time.

Effect of Weathering

The weathering (r) of soil minerals is estimated in the model by the function,

$$r = r_o 10^{-0.5(pH-pHo)} \qquad (22)$$

where r_o and pH_o are the initial conditions. An r_o value of 0.07 keq H^+ ha^{-1} yr^{-1} and a pH_o of 5.0 were applied in the equation (see Section 6.2.2).

Summary of Data Inputs

The starting parameters for soils used in simulations are given in Table 12. The taxonomy and some general descriptive features of the soils are indicated along with input data described previously. The total acid input, calculated from wetfall and dryfall acidity (from Cheng et al. 1997) is also provided in Table 12 in terms of H^+ input.

Table 12. Input Data for Soil Acidification Simulations with the ARC Model

System Definition Variables	Values					
Site	9	12	4	5	13	14
Land System	David Lake Plain	Gillespie Lowland	Sunken Lake Plain	Sunken Lake Plain	Sunken Lake Plain	Sunken Lake Plain
Soil Series	Wainwright	Metisko	Wainwright	Wainwright	Metisko	Wainwright
Soil Subgroup	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Eluviated Dark Brown Chernozem
Parent Material	Glaciofluvial	Glaciofluvial	Glaciofluvial	Glaciofluvial	Glaciofluvial	Fluvio-Eolian
Particle Size Class	Very Coarse	Moderately Coarse	Very Coarse	Very Coarse	Moderately Coarse	Very Coarse
Precipitation (cm yr^{-1})	40.0	40.0	37.6	37.6	37.6	37.6
Evapotranspiration (cm yr^{-1})	29.3	29.3	28.4	28.4	28.4	28.4
Percolation below 25 cm (cm yr^{-1})	10.7	10.7	9.2	9.2	9.2	9.2
Soil pH ($CaCl_2$)	5.5	5.4	5.5	5.6	5.3	5.5
Total Soil Bases (keq ha^{-1})	192	267	111	168	256	228
CEC (keq ha^{-1})	273	353	149	229	363	294
Base Saturation (%)	71	76	75	73	70	77
Soil Thickness (cm)	25	25	25	25	25	25
CO_2 Partial Pressure (atm)	0.005	0.005	0.005	0.005	0.005	0.005
Activity Coefficient of Al^{3+}	0.82	0.82	0.82	0.82	0.82	0.82
Activity Coefficient of Al^{2+}	0.92	0.92	0.92	0.92	0.92	0.92
a in pH = a(BS) + b	3.18	3.18	3.18	3.18	3.18	3.18
b in pH = a(BS) + b	3.14	3.14	3.14	3.14	3.14	3.14
Acid Input (keq H^+ ha^{-1} yr^{-1})	0.2	0.2	0.2	0.2	0.2	0.2
Years of Iteration	300	300	300	300	300	300
Increment of Years	20	20	20	20	20	20

Table 12. Input Data for Soil Acidification Simulations with the ARC Model (Concluded)

System Definition Variables	Values					
Site	16a	23	26	29	22	19
Land System	Grassy Island Plain	Grassy Island Plain	Grassy Island Plain	Grassy Island Plain	Loverna Plain	Mere Plain
Soil Series	Leithead	Wainwright	Wainwright	Wainwright	Metisko	Cavendish
Soil Subgroup	Dark Brown Solodized Solonetz	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Orthic Dark Brown Chernozem	Orthic Brown Chernozem
Parent Material	Glaciofluvial	Glaciofluvial	Fluvio-Eolian	Glaciofluvial	Glaciofluvial	Glaciofluvial
Particle Size Class	Moderately Coarse	Very Coarse	Very Coarse	Very Coarse	Moderately Coarse	Very Coarse
Precipitation (cm yr^{-1})	35.2	35.2	35.2	35.2	35.2	35.2
Evapotranspiration (cm yr^{-1})	27.4	27.4	27.4	27.4	27.4	27.4
Percolation below 25 cm (cm yr^{-1})	7.8	7.8	7.8	7.8	7.8	7.8
Soil pH ($CaCl_2$)	5.3	6.1	5.1	5.6	5.5	5.7
Total Soil Bases (keq ha^{-1})	200	231	100	199	295	214
CEC (keq ha^{-1})	314	289	154	292	403	289
Base Saturation (%)	64	80	65	68	73	74
Soil Thickness (cm)	25	25	25	25	25	25
CO_2 Partial Pressure (atm)	0.005	0.005	0.005	0.005	0.005	0.005
Activity Coefficient of Al^{3+}	0.82	0.82	0.82	0.82	0.82	0.82
Activity Coefficient of Al^{2+}	0.92	0.92	0.92	0.92	0.92	0.92
a in pH = a(BS) + b	3.18	3.18	3.18	3.18	3.18	3.18
b in pH = a(BS) + b	3.14	3.14	3.14	3.14	3.14	3.14
Acid Input (keq H^+ ha^{-1} yr^{-1})	0.2	0.2	0.2	0.2	0.2	0.2
Years of Iteration	300	300	300	300	300	300
Increment of Years	20	20	20	20	20	20

6.3.2 Computations

The loss of bases is calculated on an annual basis from,

$$S = I - A - C - W \quad (23)$$

where S is the sum of bases lost, I is the effective acidity in the precipitation plus dryfall (the PAI), A is the acid leached out of the top 25 cm of soil, C is the decrease in bicarbonate weathering due to the decrease in soil solution pH, and W is the base contribution due to weathering. At the end of each year of simulation, a new sum of bases is calculated from the sum for the previous year. New values for pH and Al^{3+} content are also calculated from equations relating pH with base saturation and pH with solution Al^{3+} concentration. A linear function describes the relationship between pH and base saturation percentage of the soil. The functions have been determined previously and reported by Abboud and Turchenek (1990).

The computation of BC:Al ratio was added to the model for evaluating soils in the Provost-Esther study area.

A new algorithm was added to the previously developed ARC model whereby base cations to aluminum (BC:Al) ratios in soil solution could be calculated. This procedure takes advantage of the soil's lime potential (LP) which links soil pH, base cation content (mostly Ca and Mg) and the ratio of base and acidic cations on the exchange complex (Reuss and Johnson 1986). The equation used for lime potential is as follows (Reuss and Johnson 1986):

$$\text{Lime Potential} = LP = pH - \tfrac{1}{2}\, pCa = 1/3 \log KAl + \log KS + 1/6 \log \{(ECa)3/(EAl)2\} \quad (24)$$

Where pH = soil solution pH or pH in water
pCa = -log Ca activity in soil solution
K_{Al} = Stability constant of the $Al(OH)_3$ solid phase
K_S = Gaines-Thomas selectivity constant of the Ca-Al exchange reaction
E_{Ca} = Equivalent fraction of Ca on the exchange complex
E_{Al} = Equivalent fraction of Al on the exchange complex

If one assumes that E_{Ca} and E_{Al} are equivalent to base saturation (BS) and (1-BS), then the above equation becomes:

$$\text{Lime Potential} = LP = pH - \tfrac{1}{2}\, pCa = 1/3 \log KAl + \log KS + 1/6 \log \{(BS)3/(1-BS)2\} \quad (25)$$

Using data for soil samples collected in this study, we found log K_{Al} to be 11.7 ± 0.23 while log K_S was 0.93 ± 0.39. K_{Al} was calculated from saturated paste data after speciation of the soil solution and calculating the activities of the Al^{3+} ion and using the pH values. The equation used was the same as for dissolution of $Al(OH)_3$ (gibbsite):

$$\log K_{Al} = 3pH - p(Al^{3+}) \quad (26)$$

K_S values were calculated from the K_{Al}, LP and base saturation values as per equation 25.

The model calculates lime potential using equation 25 for every time period, then uses this value to calculate the Ca (approximating base cations) activity in solution as:

$$(Ca) = 10^{(2pH - 2\,LP)} \quad (27)$$

The BC:Al ratio is then calculated from the above Ca concentration value (converted from activity) and the total Al already calculated in the model.

Another change in the model relates to the relationship between pH and Al^{3+} activity in solution. The relationship included in the previously developed ARC model was replaced with equation 26.

6.3.3 *Model Execution and Data Outputs*

Computations were made for changes in soil properties on an annual basis, but data were reported for 20-year intervals. Output data for each time interval included: (1) year; (2) pH of soil; (3) acid input; (4) acid output; (5) protonation; (6) change in pH; (7) base saturation; (8) sum of base cations; (9) base cations lost; (10) Al^{3+} concentration in soil solution, and (11) BC:Al ratio. The outputs of major interest are the changing values of soil pH, base saturation, Al^{3+} and BC:Al ratio during the 20-year and 300-year periods. Model data were transferred to EXCEL spreadsheets to facilitate data analysis in terms of critical loads. Simulations were conducted with a desktop computer.

6.3.4 *Critical Load Derivation*

It is necessary to consider the time frame within which changes in soil chemistry occur in the derivation of critical loads when one uses dynamic models, including the ARC model. Decisions are required as to whether critical chemical values of soil chemical parameters may be reached in only a few years, or over a longer period. Fifty and one hundred year time periods were selected for these decisions. Fifty years is a relatively short period, and its selection is based on the premise that it is of sufficient length to enable detection of an actual acidification trend and to initiate measures to counteract the trend. One hundred years is a longer time frame that results in a lower critical load, and it therefore provides a greater measure of protection.

The ARC model predictions of critical loads for critical chemical values reached after 50 and 100 years of acid deposition were derived from tabulated model output data for a 300 year period, and are presented in Table 13. The critical loads based on pH_c range from <0.2 to >1 keq ha^{-1} yr^{-1}. The lowest critical load was calculated for Site 26 where the initial pH was already near the critical value. The most common critical load for pHc based on a 50-year period was 1 keq ha^{-1} yr^{-1}, while that for a 100-year period was 0.5-1 keq ha^{-1} yr^{-1}. The most common critical load based on base saturation percentage (BSP) in a 50 year period was 1 keq ha^{-1} yr^{-1}, while that for a 100 year period was 0.2-0.5 keq ha^{-1} yr^{-1}. The ARC model calculations of base cation to aluminum ratio (BC:Al) were very high, resulting in estimated critical loads >1 keq ha^{-1} yr^{-1} for both 50 and 100 year time periods at all sites.

Table 13. ARC Model Predictions of Critical Loads for Critical Chemical Values Reached after 50 and 100 Years of Acid Deposition

Site/ Soil	Initial pH	Initial BSP[1]	Critical BSP[1]	50 Yr CL[2] for pH_c[3]	100 Yr CL for pH_c	50 Yr CL for BSP	100 Yr CL for BSP	50 Yr CL for BC:Al[4]	100 Yr CL for BC:Al
4	5.5	74	59	0.5	0.2-0.5	0.5	0.2-0.5	>1	>1
5	5.6	73	58	1	0.5-1	0.5-1	0.2-0.5	>1	>1
9	5.5	70	56	1	0.5-1	>1	0.2-0.5	>1	>1
12	5.4	76	61	1	0.5-1	>1	0.5-1	>1	>1
13	5.3	71	57	0.5-1	0.2-0.5	1	0.5	>1	>1
14	5.5	78	62	1	0.5-1	1	0.5-1	>1	>1
16A	5.3	64	51	0.5-1	0.2-0.5	1	0.2-0.5	>1	>1
19	5.7	74	59	>1	0.5-1	1	0.5	>1	>1
22	5.5	73	58	>1	0.5-1	>1	0.5-1	>1	>1
23	6.1	80	64	>1	>1	1	0.5-1	>1	>1
26	5.1	65	52	<0.2	<0.2	0.5	0.2-0.5	>1	>1
29	5.6	68	54	>1	0.5-1	0.5-1.0	0.2-0.5	>1	>1

1 - BSP - base saturation percentage; critical BSP is 0.8 of initial BSP; 2 - CL – critical load (keq ha^{-1} yr^{-1}); 3 - pH_c - soil pH measured in $CaCl_2$ solution; critical chemical value is 5.0 [4] BC:Al – base cation to aluminum ratio in soil solution; critical chemical value is 45. Critical chemical values are as recommended in Table 2, Section 2.2.

6.4 SMART Model

The SMART model (Section 3.3) simulates base saturation, pH and ionic contents in soil solution by combining a set of equilibrium equations with mass balance equations for the major soil ions. Al in solution is simulated with equilibrium equations, nitrification is related to NH_4 content, sulphate adsorption is based on the Langmuir adsorption mechanism, and cation exchange is calculated according to the Gaines-Thomas equilibrium (de Vries 1991). Nutrient uptake and chemical weathering are model inputs. Thus, a weathering rate for model input must be estimated by separate means as described, for example, in the SMB approach (Section 6.2.2).

6.4.1 Data Inputs

Soil Parameters

Model inputs for soil properties and other parameters for the various soils examined are listed in Table 14. Cation exchange capacity and base saturation percentages are based on the ammonium acetate method. Starting values for pH are not input parameters but are instead calculated by the model from base saturation and Al chemistry parameters.

Deposition Data

Deposition data are input as NO_3, NH_4, SO_4, BC, Na and Cl. The input values for these included both wet and dry deposition amounts as calculated by Cheng et al. (1997).

Climate Data

Precipitation data sources were as described in Sections 4.8 and 4.9.

Time

The SMART model can be executed for any specified time period, and simulation results are reported on an annual basis. Other time considerations are as indicated for the ARC model (Section 6.3.1).

Weathering

The weathering rate is a constant; it does not change with change in pH according to a function such as that used in the ARC model. The starting value for weathering used in the ARC model ($r_o = 0.07$ keq ha^{-1} yr^{-1}) was applied to a soil thickness of 0.25 m in the SMART model.

Summary of Data Inputs

The starting parameters for soils used in simulations with the SMART model are presented in Table 14.

6.4.2 Model Execution and Data Outputs

Computations for changes in soil properties were reported on an annual basis over a 300-year period of simulation. Output data for each time interval included year, pH of soil, Al^{3+}, base saturation and BC:Al ratio. Model data were transferred to EXCEL spreadsheets to facilitate data analysis in terms of critical loads. Simulations were conducted with a desktop computer.

Table 14. Input Data for Soil Acidification Simulations with the SMART Model

System Definition Variables	Value					
Site	9	12	4	5	13	14
Period of simulation (yr)	300	300	300	300	300	300
Soil bulk density (Mg m^{-3})	1.4	1.4	1.4	1.4	1.4	1.4
Thickness of the soil compartment (m)	0.25	0.25	0.25	0.25	0.25	0.25
Volumetric H_2O (m m^{-1}) (at saturation)	0.53	.53	0.49	0.47	0.59	0.61
Volumetric H_2O (m m^{-1}) (at field capacity)	0.15	0.14	0.07	0.14	0.15	0.12
Initial amount of carbonates (meq kg^{-1})	0	0	0	0	0	0
Cation exchange capacity (meq kg^{-1})	81	104	44	65	105	83
Organic matter content of topsoil (kg kg^{-1})	0.017	0.030	0.011	0.014	0.028	0.042
Initial C:N ratio in organic matter	11.0	12.6	11.1	11.2	11.7	16.3
$\log_{10}$ of selectivity constant for Al-BC exchange	1	1	1	1	1	1
$\log_{10}$ of selectivity constant for H-BC exchange	5.176	5.176	5.176	5.176	5.176	5.176
$\log_{10}$ of gibbsite equilibrium constant	8.77	8.77	8.77	8.77	8.77	8.77
Mode of initialization (1 if fBC known; 2 if fBC unknown)	1	1	1	1	1	1
Initial base saturation (fBC)	0.71	0.76	0.75	74	70	78
Nitrification factor ($0 \leq fnit \leq 1$)	1	1	1	1	1	1
De-nitrification factor ($0 \leq fden \leq 1$)	0	0	0	0	0	0
Initial Al buffer capacity (meq kg^{-1})	75	75	75	75	75	75
Maximum SO_4 adsorption capacity (meq kg^{-1})	0	0	0	0	0	0
Half-saturation constant of SO_4 adsorption (eq m^{-3})	0.1	0.1	0.1	0.1	0.1	0.1
Concentration of organic acids (DOC) (eq m^{-3})	0.1	0.1	0.1	0.1	0.1	0.1
Three parameters for modelling pKa	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039
Net Precipitation (m yr^{-1})	0.400	0.400	0.376	0.376	0.376	0.376
pCO_2 in soil solution as a multiple of pCO_2 in air (atm)	63	63	63	63	63	63
2 weathering rate parameters (BC2, BC1) (eq m^{-3} yr^{-1})	0.03, 0	0.03, 0	0.03, 0	0.03, 0	0.03, 0	0.03, 0

System Definition Variables	Value					
3 uptake parameters (N, BC2, BC1) (eq m^{-2} yr^{-1}) (For forest, N = 0.01; BC2 = 0.01; BC1 = 0; for grassland, N = 0.0; BC2 = 0.0; BC1 = 0)	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0.01, 0.01, 0
6 deposition parameters (eq m^{-2} yr^{-1})						
Sulphate deposition (SO_2)	0.015	0.015	0.015	0.015	0.015	0.015
Nitrate deposition (NO_X)*	0.005	0.005	0.005	0.005	0.005	0.005
Ammonium deposition (NH_3)*	0.010	0.010	0.010	0.010	0.010	0.010
Divalent BC deposition (BC2)	0.010	0.010	0.010	0.010	0.010	0.010
Na+K deposition (BC1)	0	0	0	0	0	0
Chloride deposition (Cl)	0	0	0	0	0	0
Site	16a	23	26	29	22	19
Period of simulation (yr)	300	300	300	300	300	300
Soil bulk density (Mg m^{-3})	1.4	1.4	1.4	1.4	1.4	1.4
Thickness of the soil compartment (m)	0.25	0.25	0.25	0.25	0.25	0.25
Volumetric H_2O (m m^{-1}) (at saturation)	0.62	0.54	0.51	0.54	0.71	0.52
Volumetric H_2O (m m^{-1}) (at field capacity)	0.08	0.13	0.09	0.15	0.18	0.13
Initial amount of carbonates (meq kg^{-1})	0	0	0	0	0	0
Cation exchange capacity (meq kg^{-1})	89	82	44	85	111	81
Organic matter content of topsoil (kg kg^{-1})	0.030	0.020	0.014	0.026	0.066	0.023
Initial C:N ratio in organic matter	12.5	12.0	12.8	12.9	13.6	11.9
$\log_{10}$ of selectivity constant for Al-BC exchange	1	1	1	1	1	1
$\log_{10}$ of selectivity constant for H-BC exchange	5.176	5.176	5.176	5.176	5.176	5.176
$\log_{10}$ of gibbsite equilibrium constant	8.77	8.77	8.77	8.77	8.77	8.77
Mode of initialization (1 if fBC known; 2 if fBC unknown)	1	1	1	1	1	1
Initial base saturation (fBC)	64	80	65	69	73	74
Nitrification factor ($0 \leq fnit \leq 1$)	1	1	1	1	1	1
De-nitrification factor ($0 \leq fden \leq 1$)	0	0	0	0	0	0
Initial Al buffer capacity (meq kg^{-1})	75	75	75	75	75	75
Maximum SO_4 adsorption capacity (meq kg^{-1})	0	0	0	0	0	0
Half-saturation constant of SO_4 adsorption (eq m^{-3})	0.1	0.1	0.1	0.1	0.1	0.1

System Definition Variables	Value					
Concentration of organic acids (DOC) (eq m^{-3})	0.1	0.1	0.1	0.1	0.1	0.1
Three parameters for modelling pKa	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039	0.96, 0.9, 0.039
Net Precipitation (m yr^{-1})	0.352	0.352	0.352	0.352	0.352	0.352
pCO_2 in soil solution as a multiple of pCO_2 in air (atm)	63	63	63	63	63	63
2 weathering rate parameters (BC2, BC1) (eq m^{-3} yr^{-1})	0.03, 0	0.03, 0	0.03, 0	0.03, 0	0.03, 0	0.03, 0
3 uptake parameters (N, BC2, BC1) (eq m^{-2} yr^{-1}) (For forest, N = 0.01; BC2 = 0.01; BC1 = 0; for grassland, N = 0.0; BC2 = 0.0; BC1 = 0)	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0
6 deposition parameters (eq m^{-2} yr^{-1})						
Sulphate deposition (SO2)	0.015	0.015	0.015	0.015	0.015	0.015
Nitrate deposition (NO_X)*	0.005	0.005	0.005	0.005	0.005	0.005
Ammonium deposition (NH_3)*	0.010	0.010	0.010	0.010	0.010	0.010
Divalent BC deposition (BC2)	0.010	0.010	0.010	0.010	0.010	0.010
Na+K deposition (BC1)	0	0	0	0	0	0
Chloride deposition (Cl)	0	0	0	0	0	0

* Cheng et al (1997) report total N. This is divided into $1/3NO_3$ and $2/3NH_4$ according to ratios in ADRP – Crossfield (Legge and Krupa 1990).

6.4.3 *Critical Load Derivation*

Derivations of critical loads using the SMART model were based on 50- and 100-year time frames, as described previously for the ARC model (Section 6.3.4). The SMART model predictions of critical loads for threshold values reached after 50 and 100 years of acid deposition are presented in Table 15. The critical loads based on pH_c range from 0.5-1 keq ha^{-1} yr^{-1} to >1 keq ha^{-1} yr^{-1}. The lowest critical loads were obtained at Sites 4 and 26. All critical loads for pH_c based on a 50-year period were >1 keq ha^{-1} yr^{-1}, while the lowest critical load for a 100 year period was 0.5-1 keq ha^{-1} yr^{-1}. The most common critical load based on base saturation percentage (BSP) in both 50 and 100-year periods was <0.2 keq ha^{-1} yr^{-1}. The SMART model calculations of base cation to aluminum ratio (BC:Al) ranged from <0.2 keq ha^{-1} yr^{-1} to>1 keq ha^{-1} yr^{-1}; consistent with the ARC model results, the lowest values were obtained for Sites 4 and 26.

Table 15. SMART Model Predictions of Critical Loads at Critical Chemical Values Reached after 50 and 100 Years of Acid Deposition

Site/ Soil	Initial pH_c[2]	Initial BSP[1]	Critical BSP[1]	50 Yr CL[3] for pH_c	100 Yr CL for pH_c	50 Yr CL for BSP	100 Yr CL for BSP	50 Yr CL for BC:Al[4]	100 Yr CL for BC:Al
4	5.5 (5.7)	74	59	>1	0.5-1	<0.2	<0.2	0.5-1	<0.2
5	5.6 (5.7)	73	58	>1	>1	<0.2	<0.2	>1	0.2-0.5
9	5.5 (5.7)	70	56	>1	>1	<0.2	<0.2	>1	0.5-1
12	5.4 (5.8)	76	61	>1	>1	<0.2	<0.2	>1	>1
13	5.3 (5.7)	71	57	>1	>1	0.2	<0.2	>1	0.5-1
14	5.5 (5.7)	78	62	>1	>1	<0.2	<0.2	>1	0.5-1
16A	5.3 (5.7)	64	51	>1	>1	<0.2	<0.2	>1	0.5-1
19	5.7 (5.7)	74	59	>1	>1	<0.2	<0.2	>1	>1
22	5.5 (5.7)	73	58	>1	>1	0.2	<0.2	>1	>1
23	6.1 (5.7)	80	64	>1	>1	<0.2	<0.2	>1	0.5-1
26	5.1 (5.7)	65	52	>1	0.5-1	<0.2	<0.2	0.5-1	<0.2
29	5.6 (5.7)	68	54	>1	>1	0.2	<0.2	>1	0.5-1

1 - Base saturation percentage; critical chemical value for BSP is 0.8 of initial BSP; 2 - pH_c - soil pH measured in $CaCl_2$ solution; critical chemical value is 5.0; the value in parenthesis is calculated by the model; 3 - CL – critical load; 4 - BC:Al – base cation to aluminum ratio in soil solution; threshold value is 45

7.0 COMPARISON OF METHODS OF CRITICAL LOAD DERIVATION

Critical loads for sandy soils in the Provost-Esther study area, as determined by the empirical, Steady State Mass Balance, ARC and SMART models are summarized in Table 16. Summary observations from Table 16 are as follows:

- The SMB approach resulted in the lowest critical load (CL) values, which were in general considerably lower than most other derived values.
- The Empirical approach provided CL values that were higher than the SMB values, and generally lower than ARC or SMART model values. However, values were similar to ARC and SMART in some instances, especially to ARC BSP_{100} and SMART $BC:Al_{100}$ values.
- The ARC model BC:Al values and derived critical loads were high as compared to the SMART BC:Al results. The differences in these values arose from the differing methods by which Al concentration is calculated in the models. The ARC model used a log K value of 11.7 for a gibbsite-like mineral that controls the solubility of Al, while the SMART model used a value of 8.77. The ARC model value was obtained from empirical data of over 30 soil samples from the study area while the SMART model used the theoretical solubility value for gibbsite.
- The SMART model values for BSP and derived critical loads were low in all instances, suggesting a flaw in BSP calculation in this model. Attempts to correct for exchange reactions resulted in inability to execute the model computer program, suggesting a probable error in the ion exchange subroutine. Communications with the authors of a new revised SMART model indicated their willingness to share the new and hopefully corrected program with us, but it was not yet available at the time of completion of this project. Therefore, further BSP calculations with the SMART could not be completed.
- The ARC model and SMART model CLs based on pH_c were similar for many sites, but somewhat lower based on the ARC model as compared to the SMART model at a few sites. For example, a low CL based on pH_c was derived at Site 26 by the ARC model. This resulted from the initial pH_c (5.1) being near the threshold level of 5.0. The SMART model, however, calculates the starting pH based on exchangeable and soil solution cation relationships. The calculated pH_c in this case was 5.7, and a considerably larger CL, as compared to the ARC value, was therefore derived. The differences in CL for Site 13 can be similarly explained.
- Similar or overlapping CLs occur in comparison of 50-year values for ARC pH_{50}, SMART pH_{50}, ARC BSP_{50} and SMART $BC:Al_{50}$. The similarities are not as consistent for the 100-year values for the same parameters (ARC pH_{100}, SMART pH_{100}, ARC BSP_{100} and SMART $BC:Al_{100}$).

Both the Empirical and SMB approaches to setting critical loads are based on maintaining steady-state over a very long time. They are based on replenishment of base cations in soil by weathering, and in the case of the SMB model, on the opposing factor of long-term cation retention in plant biomass. A considerable amount of buffering capability is provided by cations on the cation

exchange complex. For protection of soils in the relatively short term, simulation of soil chemistry based on cation exchange buffering provides more realistic predictions than methods based on weathering alone. Thus, it is considered that the ARC and SMART models should provide a relatively more realistic basis for derivation of critical loads, as compared to the empirical and SMB methods. The SMB and Empirical methods, as noted above, provided somewhat lower CLs than the ARC and SMART models. In some cases, the CLs based on the Empirical method were similar to the CLs based on 100-year periods in the ARC and SMART models. This suggests that if CLs are to be based on either or both of the ARC and SMART models, and based on the premise that any error should be on the side of caution, then the 100 year CLs would be preferable to the 50 year CLs for protecting soils.

The ARC model CLs based on pH_c were generally lower than those determined by the SMART model. It was noted above that ARC BC:Al and SMART BSP values are likely unreliable. Thus, between-model comparisons of BC:Al and BSP cannot be made. However, CLs based on ARC BSP_{100} were generally lower than those based on SMART $BC:Al_{100}$. It is concluded, therefore, on the basis of current model capabilities, that CLs derived from the ARC model are preferable to those based on the SMART model; they are lower, and therefore represent a conservative approach. However, if both models can be applied, then all of ARC pH_{100}, SMART pH_{100}, ARC BSP_{100} and SMART $BC:Al_{100}$, should be used.

7.1 Selecting the Critical Load Value

Having compared the different approaches to determining CLs, issues that must still be addressed are: (1) determination of the CL for an individual soil profile, (2) determination of the CL for a soil series (i.e., a CL for all the profiles within a soil series), and (3) mapping the CLs. Derivation of critical loads based on pH_c and BSP changes over a 100 year period as predicted by the ARC model was suggested above. Another approach, which uses both 50 and 100 year model results, and which links the critical load determinations to mapping of the loads, is described herein.

The approach links model-derived critical loads to sensitivity classes. The critical loads, or more specifically 'critical load ranges', were assigned to a sensitivity class that could more or less be equated with critical loads for application in Alberta (Clean Air Strategic Alliance and Alberta Environment 1999). These critical loads are 0.25 keq ha^{-1} yr^{-1} for sensitive soils, 0.50 keq ha^{-1} yr^{-1} for moderately sensitive soils, and 1.00 keq ha^{-1} yr^{-1} for soils of low sensitivity. The suggested critical load and sensitivity classes are as follows:

≤0.2 keq ha^{-1} yr^{-1}; critical chemical value reached within 100 years	Sensitive
0.2 to 0.5 keq ha^{-1} yr^{-1}; critical chemical value within 50 years	Sensitive
0.2 to 0.5 keq ha^{-1} yr^{-1}; critical chemical value within 100 years	Moderate sensitivity
0.5 to 1.0 keq ha^{-1} yr^{-1}; critical chemical value within 50 years	Moderate sensitivity
0.5 to 1.0 keq ha^{-1} yr^{-1}; critical chemical value within 100 years	Low sensitivity
>1.0 keq ha^{-1} yr^{-1}; critical chemical value within 50 years	Low sensitivity

Table 16. Comparison of Critical Loads Derived by Different Methods

Critical Load Derivation Method and Criterion	Critical Load (keq $ha^{-1}yr^{-1}$)					
	Aspen (Central Area)	North Grassland	North Grassland	Central Grassland	Central Grassland	Central Grassland
	Site 14 Very Coarse[1]	Site 9 Very Coarse	Site 12 Moderately Coarse	Site 4 Very Coarse	Site 5 Very Coarse	Site 13 Moderately Coarse
Empirical	0.2-0.5	0.2-0.5	0.5-1.0	0.2-0.5	0.2-0.5	0.5-1.0
SMB	0.16	0.17	0.31	0.16	0.16	0.31
ARC pH_{50}	1	1	1	0.5	1	0.5-1
SMART pH_{50}	>1	>1	>1	>1	>1	>1
ARC pH_{100}	0.5-1	0.2-0.5	0.5-1	0.2-0.5	0.5-1	0.2-0.5
SMART pH_{100}	>1	>1	>1	0.5-1	>1	>1
ARC BSP_{50}	1	>1	>1	0.5	0.5-1	1
SMART BSP_{50}	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
ARC BSP_{100}	0.5-1	0.2-0.5	0.5-1	0.2-0.5	0.2-0.5	0.5
SMART BSP_{100}	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
ARC $BC:Al_{50}$	>1	>1	>1	>1	>1	>1
SMART $BC:Al_{50}$	>1	>1	>1	0.5-1	>1	>1
ARC $BC:Al_{100}$	>1	>1	>1	>1	>1	>1
SMART $BC:Al_{100}$	0.5-1	0.5-1	>1	<0.2	0.2-0.5	0.5-1

Critical Load Derivation Method and Criterion	South Grassland	South Grassland	South Grassland	South Grassland	South Grassland	South Grassland
	Site 16a Moderately Coarse	Site 19 Very Coarse	Site 22 Moderately Coarse	Site 23 Very Coarse	Site 26 Very Coarse	Site 29 Very Coarse
Empirical	0.5-1.0	0.2-0.5	0.5-1.0	0.2-0.5	0.2-0.5	0.2-0.5
SMB	0.31	0.16	0.31	0.16	0.16	0.16
ARC pH_{50}	0.5-1	>1	>1	>1	<0.2	>1
SMART pH_{50}	>1	>1	>1	>1	>1	>1
ARC pH_{100}	0.2-0.5	0.5-1	0.5-1	>1	<0.2	0.5-1
SMART pH_{100}	>1	>1	>1	>1	0.5-1	>1
ARC BSP_{50}	1	1	>1	1	0.5	0.5-1
SMART BSP_{50}	<0.2	<0.2	<0.2	<0.2	<0.2	0.2
ARC BSP_{100}	0.5	0.5	0.5-1	0.5-1	0.2-0.5	0.2-0.5
SMART BSP_{100}	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
ARC $BC:Al_{50}$	>1	>1	>1	>1	>1	>1
SMART $BC:Al_{50}$	>1	>1	>1	>1	0.5-1	>1
ARC $BC:Al_{100}$	>1	>1	>1	>1	>1	>1
SMART $BC:Al_{100}$	0.5-1	>1	>1	0.5-1	<0.2	0.5-1

1 Very coarse - soils of sand and loamy sand texture; moderately coarse - soils of sandy loam texture, including some loamy sands having clay contents near the upper limits of the category.

The above categories of soil sensitivity indicate, for example, that if pH_e is reduced to 5.0 or if BSP is reduced to 80% of the original BSP within 100 years at a Potential Acid Input level of ≤0.2 keq ha^{-1} yr^{-1}, than the soil would be regarded as Sensitive. If 0.2 to 0.5 keq ha^{-1} yr^{-1} reduces these soil properties to the critical chemical values within 50 years, then the soil would also be regarded as sensitive. However, if 50 to 100 years is required at this latter level, than the soil would be allocated to the Moderate sensitivity class.

This approach enables the allocation of a specific soil profile to a sensitivity class. The above criteria were applied to the twelve soils to which the ARC model was applied, and compared to acidification sensitivity criteria of Holowayhuk and Fessenden (1984). Results are presented in Table 17, along with Holowayhuk and Fessenden ratings for sites having sufficient data for sensitivity class allocation. Soils to which the ARC model was not applied were allocated to a sensitivity class on the basis of similarity in pH and texture to soils that were sampled, analyzed and modelled. The similar soil is indicated in the 'Comments' column in Table 17.

The second of the issues indicated above, the determination of the CL for a soil series, requires examination of the frequency distribution of CLs (or sensitivity classes) of profiles that were examined. Table 18 indicates the number of profiles allocated to different sensitivity classes using the scheme described above. Approaches to selecting the critical load for a series involve determining the mean, mode, lowest value or a percentile of the CLs. Selection of the lowest value would afford the greatest protection for all soils, but this may be extreme because the data suggest that there are few sites with soils having very low CLs. (Soils with the lowest CLs are those with the lowest pH and/or base cation content. They occur at the extremes of the frequency distribution curve for these parameters.) The modal value would likely protect the majority of soils within a series. Another approach, which follows the CCME protocol for the development of soil quality objectives, (CCME, 1996), is to use the 25th percentile of a range of effects data as the threshold value. The data in Table 18 indicate that, based on the 'mode' of the distribution, the Wainwright series would be categorized as Moderately Sensitive. The 25th percentile would likewise place the Wainwright series in the Moderate sensitivity class. The Metisko series would be placed in the Low Sensitivity category, although there are only five replicates with which to base this conclusion. Conclusions regarding the remaining three soil series in Table 18 are much more tenuous as there is only one sample representing each series. Although the Leithead and Bingville soil profiles each were categorized as Moderately Sensitive, they are similar in texture to the Metisko series, and might best be regarded as having Low Sensitivity. The Cavendish series is similar in texture to the Wainwright series. It was characterized as being of Moderate to Low Sensitivity.

This approach to determining critical loads suggests that the Wainwright soil series is predominantly Moderately Sensitive to acidic inputs. Moderately coarse textured soils (Metisko, Leithead and Bingeville) are mainly of Low Sensitivity. The Cavendish soil was categorized as being of Moderate to Low sensitivity. This soil is the Brown soil zone equivalent of the Wainwright series, and has been described as having surface soils with slightly acid to neutral (pH (H_2O) 6.1 to 7.5) (Kjearsgaard et al. 1983). Due to its relatively high pH, and based on analysis of soils of similar pH (Table 17), the Cavendish soil series is considered to be predominantly Low in sensitivity.

Table 17. Sensitivity Classes and Critical Loads of Sampled Soils According to the ARC Model

Site Number	Soil Series	pH_c	pH_h	Texture	CEC ($cmol_c$ kg^{-1})	50 Yr CL for pH_c	100 Yr CL for pH_c	50 Yr CL for BSP	100 Yr CL for BSP	Sensitivity Class	H-F Class	Comment
1	Wainwright	5.4	6.2	S	7.0	Nd	nd	Nd	nd	M	L	Similar to 5
2	Wainwright	5.0	5.6	LS	11.9	Nd	nd	Nd	nd	S	M	Very low pH
3	Wainwright	5.6	6.2	S(f)	Nd	Nd	nd	Nd	nd	M	-	Like 14, 16A
4	Wainwright	5.5	6.2	S	4.4	0.5	0.2-0.5	0.5	0.2-0.5	M-S	H	
5	Wainwright	5.6	6.2	LS	6.5	1.0	0.5-1.0	0.5-1.0	0.2-0.5	M	L	
6	Wainwright	7.5	7.7	LS(f)	Nd	Nd	nd	Nd	nd	L	-	Alkaline pH
7	Wainwright	5.6	6.1	LS	9.6	Nd	nd	Nd	nd	M	L	Like 14, 16A
8	Wainwright	5.4	6.0	LS	Nd	Nd	nd	Nd	nd	L	-	Similar to 14
9	Wainwright	5.5	6.0	LS	8.1	1.0	0.5-1	>1.0	0.2-0.5	M-L	M	
10	Wainwright	5.1	5.5	LS	14.1	Nd	nd	Nd	nd	M	M	Very low pH; strongly buffered by CEC
11	Metisko	5.4	5.8	SL	14.9	Nd	nd	Nd	nd	L	M	Similar to 22
12	Metisko	5.4	6.0	LS	10.4	1.0	0.5-1.0	>1.0	0.5-1.0	L	M	
13	Metisko	5.3	5.8	LS	10.5	0.5-1	0.2-0.5	1.0	0.5	M	M	Similar to 2
14	Wainwright	5.3	5.9	S	8.3	1.0	0.5-1.0	1.0	0.5-1.0	M	M	
14A	Wainwright	5.4	6.1	S(f)	Nd	Nd	nd	Nd	nd	M	-	Similar to 14
15	Wainwright	5.6	6.3	S	7.5	Nd	nd	Nd	nd	M	L	Similar to 19
16	Wainwright	5.8	6.3	LS	Nd	Nd	nd	Nd	nd	M	-	Similar to 19
16A	Leithead	5.3	6.0	S	8.9	0.5-1.0	0.2-0.5	1.0	0.2-0.5	M	M	
17	Bingville	5.1	5.7	SL	19.5	Nd	nd	Nd	nd	M	L	Very low pH; strongly buffered by CEC
18	Wainwright	5.3	5.9	LS	Nd	Nd	nd	Nd	nd	M	-	Similar to 14
19	Cavendish	5.7	6.4	LS	8.1	>1.0	0.5-1.0	1.0	0.5	M-L	L	
20	Wainwright	6.1	6.4	LS(f)	Nd	Nd	nd	Nd	nd	L	-	Similar to 23

Table 17. Sensitivity Classes and Critical Loads of Sampled Soils According to the ARC Model (Concluded)

Site Number	Soil Series	pH_c	pH_h	Texture	CEC ($cmol_c$ kg^{-1})	50 Yr CL for pH_c	100 Yr CL for pH_c	50 Yr CL for BSP	100 Yr CL for BSP	Sensitivity Class	H-F Class	Comment
21	Wainwright	5.1	5.7	LS	9.2	nd	Nd	Nd	nd	S	M	Very low pH
22	Metisko	5.5	6.1	LS	11.1	>1.0	0.5-1.0	>1.0	0.5-1.0	L	L	
23	Wainwright	6.1	6.8	LS	8.2	>1.0	>1.0	1.0	0.5-1.0	L	L	
24	Wainwright	5.4	6.2	S	5.8	nd	Nd	Nd	nd	M-S	H	Similar to 4
25	Wainwright	6.0	6.7	LS(f)	nd	nd	Nd	Nd	nd	L	-	Similar to 23
26	Wainwright	5.1	5.9	S	4.4	<0.2	<0.2	0.5	0.2-0.5	S	H	
26A	Wainwright	5.5	6.4	S(f)	nd	nd	Nd	Nd	nd	M-S	-	Similar to 4
27	Wainwright	6.6	7.2	LS(f)	nd	nd	Nd	Nd	nd	L	-	High pH
28	Metisko	6.3	6.8	SL/LS	12.5	nd	Nd	Nd	nd	L	-	Similar to 23
29	Wainwright	5.6	6.2	LS	8.5	>1.0	0.5-1.0	0.5-1.0	0.2-0.5	M	L	
30	Wainwright	5.8	6.7	S	5.1	nd	nd	Nd	nd	L	L	High pH
31	Wainwright	5.9	6.6	LS(f)	nd	nd	nd	Nd	nd	L	-	Similar to 23

Abbreviations: pH_c – pH ($CaCl_2$); pH_h – pH(H_2O); CL – critical load; BSP – base saturation percentage; H-F Class – Holowaychuk-Fessenden sensitivity class - no class is indicated for soils having no CEC data; (f) – field estimate - other textures based on regressions with CEC and organic matter content; nd – not determined.

Table 18. Numbers of Sampled Soil Profiles in Different Sensitivity Classes

Soil Series	Texture Class	Number of Profiles within Sensitivity Class				
		Sensitive	Moderate Sensitivity to Sensitive	Moderate Sensitivity	Moderate to Low Sensitivity	Low Sensitivity
Wainwright	Very coarse	4	1	12	1	7
Metisko	Moderately coarse			1		4
Leithead	Moderately coarse			1		
Bingville	Moderately coarse			1		
Cavendish	Very coarse				1	

8.0 CRITICAL LOAD MAP

A map depicting the Land Systems, land cover and soil sensitivity to acid inputs in the Provost-Esther grid cell was developed based on soils and land cover information as described in Sections 4.3 and 5.3. The soil rating for sensitivity to acid inputs, as determined in the previous section, was superimposed on this information. Most of the soils sampled in the area were of the Wainwright series, which mainly fell into the Moderate sensitivity class. Soils of the Metisko series, having slightly higher clay contents than the Wainwright soils, fell into the Low sensitivity category. The Leithead and Bingville soils likewise fell into this category. All soils finer in texture than Metisko soils were considered to also have Low sensitivity to acidification.

Proportions of soil series within Land Systems were estimated from information provided in Table 3, and from this, the proportions of soils in Moderate or Low acidification sensitivity categories were derived. (Greater detail is provided in Appendix Table D1.) No soils were assigned to the Sensitive category. Land Systems with predominately Moderate sensitivity soils were differentiated from those with predominantly Low sensitivity soils, and from those with similar proportions of Low and Moderate sensitivity soils. These three sensitivity categories (Low, mixture of Moderate and Low, and Moderate) were identified by colour coding on the critical loads map. The map legend is presented on the map, as well as in Table 19.

The Land Systems in the study area which were designated as having Moderate or a mixture of Moderate and Low sensitivity are as follows:

David Lake Plain: Characterized by co-dominant Metisko and Wainwright soils, and therefore indicated on the map as having a combination of Moderate and Low sensitivity classes.

Gillespie Lowland: Characterized by co-dominant Metisko and Dolcy Soils. The latter soils are like ***Wainwright*** in their surface layers. The Land System is therefore mapped as a combination of Moderate and Low sensitivity soils.

Sunken Lake Plain: Wainwright and Metisko are common soils in this Land System. Field observations ***during*** the course of this project suggested that the proportion of Wainwright soils was at least 60%. Therefore, the map shows this Land System as Moderately sensitive. It was noted in Section 5.4.1 that soils in wooded, lower slope landscape positions could have lower pH and greater sensitivity to acidic inputs as compared to soils in upper landscape positions, particularly within this Land System. The soil at Site 2, which was the lower slope counterpart of Site 1, in fact had a Sensitive rating (Table 17). Another upper slope/lower slope pair (Sites 14a and 14b) had a Moderate sensitivity rating in both landscape positions. Occurrence of Sensitive soils cannot, therefore, be correlated with lower landscape position. About 15 percent of all Wainwright soils that were sampled in the study area had Sensitive ratings (Table 18). Only one of the sites was situated in

a lower slope position. Therefore, the extent of lower slope Sensitive soils is estimated to be quite low (in the order of 5 percent), but the overall extent of Sensitive soils in the Sunken Lake Plain appears to be about 15 percent.

Grassy Island Plain: This Land System is dominated by Wainwright soils with Moderate sensitivity.

Loverna Plain: ***Wainwright*** and Metisko soils occur in more or less equal proportions, and the map is coded as being a mixture of Moderate and Low sensitivity soils.

Table 19. Map Legend - Land Systems, Land Cover and Soil Sensitivity to Acid Inputs in the Provost-Esther Grid Cell

LAND SYSTEM SYMBOL	LAND SYSTEM NAME	SOIL ZONE	MAJOR SOIL SERIES	MINOR SOIL SERIES	ACIDIFICATION SENSITIVITY (% of Area)	GENERAL DESCRIPTION
01.3d.01	Sounding Valley	Brown	Bingville (Orthic Brown Chernozem) Ronalaine (Solonetzic Brown Chernozem)	Bullpound (Brown Solonetz) Dishpan (Rego Gleysol)	Low - 100%	Landscape is undulating with some floodplain. Brown Chernozems developed on moderately coarse textured glaciofluvial sediments and medium textured till. Minor Solonetz and Gleysols.
01.3d.02	Sedalia Plain	Brown	Hemaruka (Brown Solodized Solonetz) Halliday (Brown Solod)	Maleb (Orthic Brown Chernozem) Cecil (Solonetzic Brown Chernozem)	Low - 100%	Landscape is undulating with some hummocky. Brown Solonetz developed on moderately fine textured till. Minor Chernozems.
01.4d.02	Calendula Upland	Brown	Maleb (Orthic Brown Chernozem) Foremost (Orthic Brown Chernozem)	Hemaruka (Brown Solodized Solonetz) Ronalaine (Solonetzic Brown Chernozem)	Low - 100%	Landscape is hummocky. Brown Chernozems developed on moderately fine textured till. Minor Solonetz.

LAND SYSTEM SYMBOL	LAND SYSTEM NAME	SOIL ZONE	MAJOR SOIL SERIES	MINOR SOIL SERIES	ACIDIFICATION SENSITIVITY (% of Area)	GENERAL DESCRIPTION
01.4d.18	Salt Lake Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Neutral (Rego Dark Brown Chernozem) Onnevue (Solonetzic Dark Brown Chernozem)	Low - 100%	Landscape is hummocky with some ridged. Dark Brown Chernozems developed on moderately fine textured till. Significant eroded soils.
01.4f.02	Sibbald Plain	Brown	Chin (Orthic Brown Chernozem)	Acadia Valley (Calcareous Brown Chernozem) Maleb (Orthic Brown Chernozem)	Low - 100%	Landscape is undulating with some hummocky. Brown Chernozems on medium textured glaciolacustrine sediments. Minor fine textured soils.
01.4f.03	Mere Plain	Brown	Bingville (Orthic Brown Chernozem) Pemukan (Orthic Brown Chernozem)	Cavendish (Orthic Brown Chernozem) Chin (Orthic Brown Chernozem)	Moderate - 10% Low - 90%	Landscape is undulating. Brown Chernozems developed on moderately coarse and gravelly, very coarse glaciofluvial sediments.
02.4a.04	Pacific Creek Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Flagstaff (Solonetzic Dark Brown Chernozem)	Low - 100%	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till.
02.4a.05	Grassy Island Plain	Dark Brown	Wainwright (Orthic Dark Brown Chernozem)	Metisko (Orthic Dark Brown Chernozem) Gough Lake (Rego Gleysol)	Moderate - 80% Low - 20%	Landscape is undulating with some level, closed basin and duned. Dark Brown Chernozems on very coarse textured fluvioeolian sediments. Minor Gleysols and fine textured soils.
02.4a.06	Loverna Plain	Dark Brown	Metisko (Orthic Dark Brown Chernozem) Wainwright (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem)	Moderate - 50% Low - 50%	Landscape is undulating with some duned and hummocky. Dark Brown Chernozems developed on coarse textured glaciofluvial and very coarse textured fluvioeolian sediments.

LAND SYSTEM SYMBOL	LAND SYSTEM NAME	SOIL ZONE	MAJOR SOIL SERIES	MINOR SOIL SERIES	ACIDIFICATION SENSITIVITY (% of Area)	GENERAL DESCRIPTION
02.4a.08	Altario Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Kirriemuir (Orthic Dark Brown Chernozem) Altario (Rego Dark Brown Chernozem)	Low - 100%	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till. Significant eroded soils.
05.2a.01	St. Lawrence Hills	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Gleysols Provost (Orthic Dark Brown Chernozem)	Low - 100%	Landscape is undulating with some hummocky and ridged. Dark Brown Chernozems on moderately fine textured till. Minor Gleysols.
05.2a.02	Gillespie Lowland	Dark Brown	Metisko (Orthic Dark Brown Chernozem) Dolcy (Orthic Dark Brown Chernozem)	Wainwright (Orthic Dark Brown Chernozem) Gleysols	Moderate - 30% Low - 70%	Landscape is undulating with some confined floodplain and numerous water bodies. Dark Brown Chernozems on moderately coarse textured glaciofluvial sediments and coarse textured glaciofluvial materials over moderately fine textured till. Minor Gleysols.
05.2a.03	Black Creek Upland	Dark Brown	Hughenden (Orthic Dark Brown Chernozem)	Provost (Orthic Dark Brown Chernozem) Gleysols	Low - 100%	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till. Minor Gleysols.
05.2a.04	Falcon Plain	Dark Brown	Hughenden (Orthic Dark Brown Chernozem) Provost (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem) Solonetzic soils	Low - 100%	Landscape is hummocky with some undulating. Dark Brown Chernozems developed on moderately fine textured till and medium textured material over moderately fine textured till. Minor Solonetz.

LAND SYSTEM SYMBOL	LAND SYSTEM NAME	SOIL ZONE	MAJOR SOIL SERIES	MINOR SOIL SERIES	ACIDIFICATION SENSITIVITY (% of Area)	GENERAL DESCRIPTION
05.2a.07	Hansman Plain	Dark Brown	Coronation (Orthic Dark Brown Chernozem) Provost (Orthic Dark Brown Chernozem)	Metisko (Orthic Dark Brown Chernozem) Solonetzic soils	Low - 100%	Landscape is undulating with some hummocky. Dark Brown Chernozems developed on medium textured glaciofluvial sediments and medium textured materials over moderately fine textured till. Minor Solonetz and coarse textured soils.
05.2b.07	Sunken Lake Plain	Dark Brown	Wainwright (Orthic Dark Brown Chernozem) Metisko (Orthic Dark Brown Chernozem) Houcher (Rego Dark Brown Chernozem)	Dolcy (Orthic Dark Brown Chernozem) Gleysols	Moderate - 60% Low - 40%	Landscape is duned with some undulating. Dark Brown Chernozems developed on very coarse to coarse textured glaciofluvial and fluvioeolian sediments. Minor Gleysols. Significant eroded soils.
05.2b.09	David Lake Plain	Dark Brown	Metisko (Orthic Dark Brown Chernozem) Wainwright (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem) Monitor (Rego Dark Brown Chernozem)	Moderate - 40% Low - 60%	Landscape is undulating. Dark Brown Chernozems on moderately coarse textured glaciofluvial sediments. Significant eroded soils.

Sounding Valley and Mere Plain: In spite of a Moderate sensitivity rating determined for two sites sampled from these Land Systems, the soils are considered to have predominantly Low sensitivity because of the dominance of the moderately coarse textured Bingville series. Moreover, these Land Systems were found to be mainly cultivated, with fewer areas of grassland vegetation than indicated by the PFRA land use information.

Areas of Land Systems in the study area, and of their various land types or uses, are presented in Table 20. Information in this table enables the calculation of the total estimated area, and percent of total area, of soils with Moderate acidification sensitivity in the grid cell. Applying the estimates of proportions of Moderate sensitivity soils in each Land System (Table 19) to areas of the Land Systems (Table 20) results in an estimate of 715.0 km^2, or 18.7%, of the Provost-Esther grid cell, that are characterized by sandy soils of Moderate sensitivity to acid deposition. If only the areas

under Grassland, Shrubland or Treed cover are considered, then the estimate is 429.2 km^2, or 11.2% of the grid cell.

Areas of Moderate acidification sensitivity are those having critical loads of 0.2 to 0.5 keq ha^{-1} yr^{-1} within a 100 year period, or of 0.5 to 1.0 keq ha^{-1} yr^{-1} within a 50 year period. According to the Acid Deposition Management Framework (Clean Air Strategic Alliance and Alberta Environment 1999), if the total of the Sensitive and Moderately sensitive area equals or exceeds 5% of a grid cell area, the entire grid cell is classified as Moderately sensitive to acid deposition. The critical load of acidity for moderately sensitive soils is 0.5 keq ha^{-1} yr^{-1} (Clean Air Strategic Alliance and Alberta Environment 1999). Although the critical loads derived in this study are defined as ranges of acid deposition, the provincial CL for Moderately sensitive soils is within this range, and the entire Provost-Esther grid cell should be regarded as Moderately sensitive for purposes of acid deposition management.

Table 20. Areas of Land Systems and Land Cover Types

Land System	LS (km^2)	LS (%)	Water (km^2)	Water (%)	Treed Land (km^2)	Treed Land (%)	Shrubland (km^2)	Shrubland (%)	Grassland (km^2)	Grassland (%)	Cultivated (km^2)	Cultivated (%)
01.3d.01	112.59	2.95	1.83	1.63	0.09	0.08	2.36	2.09	98.23	87.25	10.09	8.96
01.3d.02	143.06	3.75	1.06	0.74	0.01	0.01	1.16	0.81	64.38	45.00	76.45	53.44
01.4d.02	81.18	2.13	0.81	1.00	0.01	0.01	0.57	0.71	24.10	29.69	55.68	68.59
01.4d.18	181.14	4.75	2.30	1.27	0.00	0.00	1.27	0.70	100.37	55.41	77.20	42.62
01.4f.02	62.30	1.63	0.54	0.86	0.04	0.07	0.10	0.15	20.32	32.61	41.31	66.31
01.4f.03	20.69	0.54	0.18	0.85	0.00	0.00	0.12	0.60	3.60	17.42	16.79	81.14
02.4a.04	115.90	3.04	1.25	1.08	0.05	0.04	1.65	1.43	73.58	63.48	39.37	33.97
02.4a.05	354.16	9.28	23.89	6.75	0.21	0.06	7.38	2.08	265.56	74.98	57.13	16.13
02.4a.06	365.57	9.58	11.44	3.13	0.00	0.00	6.12	1.68	196.04	53.63	151.97	41.57
02.4a.08	913.07	23.92	13.06	1.43	0.00	0.00	43.03	4.71	609.76	66.78	247.23	27.08
05.2a.01	168.43	4.41	1.68	1.00	0.00	0.00	5.48	3.25	13.00	7.72	148.27	88.03
05.2a.02	73.73	1.93	6.22	8.44	0.04	0.05	5.79	7.85	29.28	39.71	32.41	43.95
05.2a.03	241.93	6.34	1.35	0.56	0.05	0.02	3.72	1.54	25.50	10.54	211.31	87.34
05.2a.04	305.67	8.01	8.41	2.75	0.06	0.02	2.18	0.71	12.36	4.04	282.67	92.48
05.2a.07	288.99	7.57	13.90	4.81	0.00	0.00	7.44	2.58	62.18	21.52	205.46	71.10
05.2b.07	346.48	9.08	23.28	6.72	0.00	0.00	45.93	13.26	227.04	65.53	50.22	14.50
05.2b.09	41.99	1.10	1.95	4.64	0.00	0.00	1.63	3.89	15.20	36.20	23.21	55.28
Total	**3816.88**	**100.00**	**113.15**	**2.96**	**0.56**	**0.01**	**135.94**	**3.56**	**1840.48**	**48.22**	**1726.75**	**45.24**

9.0 RECOMMENDED PROTOCOL FOR SITE-SPECIFIC CRITICAL LOAD DETERMINATION

A major objective of investigating critical loads in the Provost-Esther grid cell was to provide a recommendation and rationale regarding the most appropriate methods and receptor model to be used for determining critical loads for the soil type/land use/aquatic units investigated. A discussion in support of use of dynamic models as opposed to the empirical and SMB approaches was presented in Section 7. Of the two dynamic models examined, the ARC model is recommended for determining critical for the following reasons: 1) The methods of calculating pH, base saturation percentage, Al concentration and BC:Al ratios differ between the two models. The ARC model bases the calculations on semi-empirical relationships derived from data for soils in Alberta while the SMART model uses "theoretical" process constants that are not consistent with Alberta data. 2) The critical loads derived from the ARC model results were generally lower than those from the SMART model. Thus, a conservative approach to determining critical loads would be to apply the ARC model. 3) The accessibility of the ARC model allows us to update the model code when new data becomes available or new processes are to be considered.

The recommended protocol for site-specific critical load determinations is as follows:

- Review of available soil, climate, water and other ecological information (e.g. vegetation, land use) for the area of concern.

- Assessment of data gaps and identification of data needs. In this study, we found that the soil survey report data on cation exchange were not adequate for our purposes. Existing databases included only a small number of samples, and of some required parameters are not contained within existing databases (e.g. base saturation based on neutral salt extraction).

- Development of a field sampling protocol and acquisition of the needed data through field sampling and laboratory analysis. An issue of concern can be the number of samples required to adequately represent the area of study.

- Modeling the effects of acidifying substances on the soils of the area; at this time the ARC model is the most appropriate model for use in deriving critical loads for Alberta soils. A critical issue is the representativeness of the model parameters and processes with regard to the area of concern.

- Derivation of critical loads for each soil or soil group considered. A factor to be considered here is the time frame accepted as a base for effect identification. This is evident when comparing the 50- versus 100-year predictions outlined previously.

- Extrapolation of the critical loads from individual soil samples to soil map units. Distribution of critical loads within a map unit should be considered and an appropriate measure adopted (e.g. this study used modal values and 25^{th} percentiles as contrasted to using lowest values).

- Generation of "new" soil maps representing the acid sensitivity class(es) derived through modelling.

- Generation of reports on the distribution of critical loads within the area of concern.

10.0 CONCLUSIONS

The two objectives for this project were to develop a protocol for the derivation of critical loads for areas within the province, and to derive a critical load for the Provost-Esther grid cell, and area identified as being potentially at risk due to acid deposition.

A protocol for derivation of critical loads for Alberta grassland soils was developed, and implemented in this project. This protocol is presented in Section 9.0. Any future critical load derivations in Alberta should begin with this protocol, which may be adjusted to fit the environment and area under study.

The second objective of this study was to derive a critical load for the Provost-Esther grid cell, an area identified as being in exceedance of the cell's assigned Monitoring Load (Clean Air Strategic Alliance and Alberta Environment 1999). The results of this study indicate that the critical load for this cell is between 0.5 and 1.0 keq H^+ ha^{-1} yr^{-1}. As defined in the Acid Deposition Management Framework (Clean Air Strategic Alliance and Alberta Environment 1999), this finding supports the reassignment of this grid cell from a Sensitive to a Moderate sensitivity rating.

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APPENDIX A

SOIL PROFILE DESCRIPTIONS

SITE 1

Location: LSD 4 – Section 35 – Township 37 – Range 4 – West 4 Meridian
Classification:
Subgroup: Dark Brown Chernozem
Series: Wainwright
Landform:
Genetic Material: Glaciofluvial; some eolian in area
Surface Expression: Undulating to hummocky; 5-7% slopes
Drainage/ Perviousness: Rapidly drained; high perviousness
Site Features: Site located on gentle southeast slope; upper slope position; non-stony
Vegetation: Native grasses, wild rose, sage

Profile Description:

Ah	0 to 17 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; gradual, smooth boundary.
Bm	17 to 50 cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, very fine roots; no coarse fragments.

SITE 2
(Downslope from Site 1)

Location: *LSD 4 – Section 35 – Township 37 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating to hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Located in shallow draw downslope from Site 1; toe slope position; 5-7% slope; east aspect; non-stony*
Vegetation: *Aspen, wild rose, buckbrush, grasses*

Profile Description:

LFH	7 to 0 cm	Dark brown to black; leaf and root litter; sand mixed into lower part of litter
Ah, Ahe	0 to 12 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; gradual, smooth boundary.
Bm	12 to 50 cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, very fine roots; no coarse fragments.

SITE 3

Location: *LSD 2 – Section 29 – Township 37 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Eluviated Eutric Brunisol*
Series: *Wainwright (Brunisol variant)*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 6-7% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Gentle south-east slope; mid position; south-east aspect; non-stony; soil appears disturbed in places – may have been cleared long ago*
Vegetation: *Aspen, saskatoon berry, wild rose, pincherry, chokecherry, buffalo berry, bearberry, honeysuckle, grasses, lily-of-the-valley, northern bedstraw, buck bean, aster, vetch*

Profile Description:

LFH	3 to 0 cm	Dark brown to black; leaf mat underlain by turfy, fibrous material
Ah	0 to 8 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; litter mixed into top of layer; abundant, fine to coarse roots; no coarse fragments; clear, smooth boundary.
Ae	8 to 25 cm	Light grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; plentiful, fine to coarse roots; no coarse fragments; clear, smooth boundary.
Bm	25 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, fine roots; no coarse fragments.

SITE 4

Location: *LSD 12 – Section 22 – Township 36 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating to hummocky; 2-10% slopes (long slopes with local micro-hummocky topography)*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Located on northwest aspect of 4% slope; mid slope position; non-stony*
Vegetation: *Native grasses, wild rose, sage, wolf willow; area likely cleared of trees long ago; other parts of landscape are almost totally tree-covered*

Profile Description:

Ah	0 to 28 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; gradual, smooth boundary.
Bm	17 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, fine roots; no coarse fragments.

SITE 5

Location: *LSD 4 – Section 23 – Township 36 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Hummocky to rolling; 6-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southeast aspect of 8% slope; mid slope position; non-stony*
Vegetation: *Native grasses, wild rose, wolf willow, sage; grazed*

Profile Description:

Ah	0 to 16 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand to loamy sand; some coarse sand and fine gravel; single grain; loose; slightly cemented due to dryness; no coarse fragments; plentiful, very fine to fine roots; gradual, smooth boundary.
Bm	16 to 50+ cm	Brown (10YR 4/3 dry); sand to loamy sand; some coarse sand and fine gravel; single grain; loose; plentiful, very fine to fine roots.

SITE 6
(Downslope from Site 5)

Location: *LSD 4 – Section 23 – Township 36 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Hummocky to rolling; 6-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Toe slope position below Site 5; slopes about 3 to %; non-stony; thick Ah may have developed by accretion of material eroded by wind and water from upslope areas; Ah2 has mixed Ah and Bm materials.*
Vegetation: *Buck brush, wolf willow, wild rose, grasses, several forbs*

Profile Description:

Ah1	0 to 16 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand to loamy sand; very weak granular; very friable.
Ah2	16 to 50+ cm	Dark grayish brown (10YR 4/3 dry); sand to loamy sand; single grain; loose; no coarse fragments.

SITE 7

Location: *LSD 9 – Section 27 – Township 39 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 3% slope; mid slope position; non-stony*
Vegetation: *Native grasses and forbs, wild rose, sage; about 20% of area under wolf willow.*

Profile Description:

Ah	0 to 32 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand to loamy sand; very weak granular to fine prismatic; very friable; no coarse fragments.
Bm	32 to 50+ cm	Brown (10YR 4/3 dry); sand to loamy sand; single grain; loose; no coarse fragments.

SITE 8

Location: *LSD 2 – Section 3 – Township 41 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 3% slope; mid slope position; non-stony; near aspen stand; thick A horizon possibly due to accretion of windblown material*
Vegetation: *Grasses and forbs, wild rose, sage*

Profile Description:

Ah1	0 to 25 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand to loamy sand; weak, fine prismatic braking to weak granular and single grain; very friable; no coarse fragments.
Ah2	25 to 50 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand to loamy sand; weak, fine prismatic braking to weak granular and single grain; very friable; no coarse fragments.

SITE 9

Location: *LSD 14 – Section 34 – Township 39 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Orthic Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 2-3% slope; mid position; non-stony; about 10 m from aspen stand*
Vegetation: *Grasses, sage; some wolf willow nearby*

Profile Description:

Ah	0 to 32 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand to loamy sand; very weak, fine prismatic; very friable; no coarse fragments.
Bm	25 to 50+ cm	Brown (10YR 4/3 dry); sand to loamy sand; single grain; loose; no coarse fragments.

SITE 10

Location: *LSD 3 – Section 6 – Township 41– Range 3 – West 4 Meridian*
Classification:
Subgroup: *Orthic Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial overlying glacial fluviolacustrine*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 3% slope; mid slope position; non-stony*
Vegetation: *Native grasses, sage; buckbrush and wolf willow nearby*

Profile Description:

Ah	0 to 17 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand; moderate, medium granular; very friable; no coarse fragments.
Bm 1	17 to 30 cm	Brown (10YR 4/3 dry); loamy sand; very weak, fine subangular blocky to single grain; very friable; no coarse fragments.
Bm 2	30 to 70 cm	Brown; loamy sand; single grain; loose
IICk	70 to 100 cm	Dark yellowish brown; clay loam; massive

SITE 11

Location: *LSD 12 – Section 11 – Township 39 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Metisko*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 5-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 5% slope; lower to mid slope position; non-stony*
Vegetation: *Native grasses, wild rose, wolf willow, buckbrush*

Profile Description:

Ah	0 to 32 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand; very weak subangular blocky and granular; no coarse fragments.
Bm	32 to 50+ cm	Brown (10YR 4/3 dry); loamy sand; very weak, fine prismatic breaking to weak granular and single grain; very friable to loose; no coarse fragments.

SITE 12

Location: *LSD 15 – Section 13 – Township 39 – Range 2 – West 4 Meridian*
Classification:
Subgroup: *Orthic Dark Brown Chernozem*
Series: *Metisko (borderline Wainwright)*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *West aspect of 3% slope; mid slope position; non-stony*
Vegetation: *Grasses, sage, wild rose, buckbrush*

Profile Description:

Ah	0 to 23 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand; very weak subangular blocky and granular; no coarse fragments.
Bm	23 to 50+ cm	Brown (10YR 4/3 dry); loamy sand; very weak, fine prismatic breaking to weak granular and single grain; very friable to loose; no coarse fragments.

SITE 13

Location: *LSD 2 – Section 1 – Township 38 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Orthic Dark Brown Chernozem*
Series: *Metisko*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating, with scattered hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 2% slope; mid slope position; non-stony; stone-topped hummock north of site*
Vegetation: *Grasses, sage, buckbrush*

Profile Description:

Ah	0 to 20 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand to sandy loam; dry and hard; breaks to subangular blocky fragments; a few coarse fragments.
Bm	25 to 50+ cm	Brown (10YR 4/3 dry); sandy loam; weak, fine prismatic; very friable; abundant coarse fragments (gravel, stones) below 40 cm.

SITE 14

Location: *LSD 9 – Section 31 – Township 36 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Eluviated Dark Brown Chernozem*
Series: *Wainwright – Eluviated variant*
Landform:
Genetic Material: *Eolian*
Surface Expression: *Hummocky (duned); 10-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Near crest of 10-15% slope; non-stony*
Vegetation: *Aspen, saskatoon berry, bearberry, forbs, minor grasses*

Profile Description:

LF	4 to 0 cm	Dark brown to black; leaf and grass litter
Ahe	0 to 12 cm	Dark grayish brown (10YR 3.5-4/2 dry) (salt-and-pepper colours); sand; single grain; loose
Ae	12 to 26 cm	Light grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose
Bm	26 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose.

SITE 14a
(Downslope from 14)

Location: *LSD 9 – Section 31 – Township 36 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Eluviated Eutric Brunisol*
Series: *Wainwright – Brunisol variant*
Landform:
Genetic Material: *Eolian*
Surface Expression: *Hummocky; 10-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Northeast aspect of 6-8% slope; toe slope position; non-stony*
Vegetation: *Aspen, saskatoon berry, bearberry, forbs, minor grasses*

Profile Description:

LF	6 to 0 cm	Dark brown to black; leaf and grass litter
Ahe	0 to 16 cm	Dark grayish brown (10YR 3.5-4/2 dry) (salt-and-pepper colours); sand; single grain; loose
Ae	16 to 35 cm	Light grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose
Bm	35 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose.

SITE 15

Location: *LSD 4 – Section 25 – Township 34 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *South aspect of 6-7% slope; mid slope position; non-stony*
Vegetation: *Grasses, wild rose, buckbrush; aspen in low areas*

Profile Description:

Ah	0 to 26 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; no coarse fragments.
Bm	26 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; no coarse fragments.

SITE 16

Location: *LSD 15 – Section 22 – Township 33 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Orthic Dark Brown Chernozem*
Series: *Wainwright – Saline variant*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *South-east aspect 0f 5-7% slope; mid slope position; non-stony; low-lying, saline area nearby, north of road*
Vegetation: *Grasses, sage, buckbrush; non-grazed 'prairie wool'.*

Profile Description:

Ah	0 to 8 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand to sandy loam; weak granular; no coarse fragments.
Bm	25 to 50+ cm	Brown (10YR 4/3 dry); loamy sand to sandy loam; weakly structured, breaking to weak , subangular blocky; white spots (salts) at base of layer; no coarse fragments.

SITE 16a
(Upslope from Site 16)

Location: *LSD 15 – Section 22 – Township 33 – Range 4 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Solodized Solonetz*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 5-7% slope; upper slope to crest position; non-stony*
Vegetation: *Grasses, sage, buckbrush; non-grazed 'prairie wool'.*

Profile Description:

Ah	0 to 16 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand; very weak granular; very friable; no coarse fragments.
Bm	16 to 30 cm	Brown (10YR 4/3 dry); loamy sand; weak, fine subangular blocky; no coarse fragments.
Bnt	30 to 50+ cm	Very dark grayish brown (10YR 4/3 dry); sandy loam to loam; round topped columnar; no coarse fragments.

SITE 17

Location: *LSD 13 – Section 34 – Township 30 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Orthic Brown Chernozem*
Series: *Bingville*
Landform:
Genetic Material: *Glaciofluvial overlying glacial till*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Nearly level site; 1-2%s slopes; slightly stony*
Vegetation: *Native grasses, sage; heavily grazed; appears to have been broken at one time*

Profile Description:

Ah	0 to 12 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand to sandy loam; weak granular; very friable; few coarse fragments.
Bm	12 to 35 cm	Brown (10YR 4/3 dry); loamy sand to sandy loam; weak, medium prismatic; very friable; few coarse fragments.
Ck	35 to 40+ cm	Brown (10YR 4/3 dry); sandy loam to loam; hard; common coarse fragments.

SITE 18

Location: *LSD 2 – Section 29 – Township 30 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating to hummocky; 2-9% slopes;*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southeast aspect of 3-4% slope; mid slope position; non-stony*
Vegetation: *Grasses, sage, buckbrush*

Profile Description:

Ah	0 to 18 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; gradual, smooth boundary.
Bm 1	18 to 60 cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, fine roots; no coarse fragments.
Bm 2	60 to 80 cm	Brown (10YR 4/3 dry); sand; single grain; loose; very few roots; no coarse fragments.
Ck	80 to 100 cm	Dark yellowish brown; sand; single grain; loose; no roots; no coarse fragments.

SITE 19

Location: *LSD 4 – Section 28 – Township 29 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Orthic Brown Chernozem*
Series: *Cavendish*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *North aspect of 4% slope; upper slope position; southeast aspect; non-stony*
Vegetation: *Aspen, saskatoon berry, wild rose, pincherry, chokecherry, buffalo berry, bearberry, honeysuckle, grasses, lily-of-the-valley, northern bedstraw, buck bean, aster, vetch*

Profile Description:

Ah	0 to 12 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, fine roots; no coarse fragments.
Bm	12 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, fine roots to very few roots in lower Bm; no coarse fragments.

SITE 20

Location: *LSD 18 – Section 9 – Township 31 – Range 1– West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial overlying glacial till*
Surface Expression: *Hummocky; 9-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Northwest aspect of 10-15% slope; upper slope position; slightly stony*
Vegetation: *Aspen, native grasses, wild rose*

Profile Description:

Ah	0 to 12 cm	Dark grayish brown (10YR 3.5-4/2 dry); loamy sand; weak granular; very friable; very few coarse fragments.
Bm	17 to 50+ cm	Brown (10YR 4/3 dry); loamy sand; weak, medium prismatic; very friable; few coarse fragments.
IICk	17 to 50+ cm	Dark yellowish brown (10YR 4/3 dry); loam; massive; single grain; loose; few to many coarse fragments.

SITE 21

Location: *LSD 7 – Section 17 – Township 33 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 3% slope; mid slope position; non-stony; located on plain of Grassy Island Lake; elevation about 2-3 m about lake bed*
Vegetation: *Native grasses, sage, some buckbrush*

Profile Description:

Ah	0 to 18 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; gradual, smooth boundary.
Bm	18 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, very fine roots; no coarse fragments.

SITE 22

Location: *LSD 10 – Section 34 – Township 31 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 2-9% slopes; mainly hummocky in area slopes to 15%*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Middle of long 6-9% slope; southeast aspect; non-stony*
Vegetation: *Grasses, buckbrush*

Profile Description:

Ah	0 to 8 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; no coarse fragments.
Bm	8 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; no coarse fragments.

SITE 23

Location: *LSD 7 – Section 33 – Township 31 – Range 2 – West 4 Meridian*
Classification:
Subgroup: *Orthic dark Brown Chernozemic*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating to hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *South-east aspect of 4-5% slope; mid slope position; non-stony; may have been cleared long ago*
Vegetation: *Grasses, buckbrush, sage*

Profile Description:

Ah	0 to 16 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; no coarse fragments.
Bm	25 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; no coarse fragments.

SITE 24

Location: *LSD 16 – Section 27 – Township 32 – Range 2 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating to hummocky; 2-9% slopes (locally hummocky topography)*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 2% slope; mid slope position; non-stony*
Vegetation: *Native grasses, wild rose, sage*

Profile Description:

Ah	0 to 18 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; gradual, smooth boundary.
Bm	18 to 50+ cm	Dark grayish brown (10YR 4/3 dry); sand; single grain; loose; few, fine roots; no coarse fragments.

SITE 25

Location: *LSD 1 – Section 3 – Township 33 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial overlying glacial till; some eolian in area*
Surface Expression: *Undulating to hummocky; 10-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 15% slope; upper slope position; non-stony*
Vegetation: *Native grasses, wild rose, buckbrush*

Profile Description:

Ah	0 to 14 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; very few coarse fragments; gradual, smooth boundary.
Bm	14 to 36 cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, very fine roots; very few coarse fragments.
Ck	36 to 50+ cm	Dark yellowish brown (10YR 4/3 dry); loam; massive; friable; few coarse fragments.

SITE 26

Location: *LSD 14 – Section 36 – Township 32 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Eolian*
Surface Expression: *Hummocky (duned); 6-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *North aspect of 5% slope; lower slope position; non-stony; area is duned with some blow-outs*
Vegetation: *Aspen, wild rose, buckbrush, grasses*

Profile Description:

Ah	0 to 16 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; abundant, very fine to fine roots; no coarse fragments; clear, smooth boundary.
Bm	16 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, very fine roots; no coarse fragments.

SITE 26a
(Upslope from Site 26)

Location: *LSD 14 – Section 36 – Township 32 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Eolian*
Surface Expression: *Hummocky (duned); 6-15% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 10% slope; upper slope to crest slope position; non-stony; area is duned with some blow-outs*
Vegetation: *Aspen, wild rose, buckbrush, grasses*

Profile Description:

Ah	0 to 12 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; no coarse fragments.
Bm	12 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; few, no coarse fragments.

SITE 27

Location: *LSD 16 – Section 31 – Township 32 – Range 1 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5%*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 3-4% slope; upper slope position; non-stony*
Vegetation: *Native grasses, buckbrush, wolf willow, sage; may have been broken in a long time ago.*

Profile Description:

Ah	0 to 18 cm	Dark grayish brown (10YR 3.5-4/2 dry); gravelly sand; single grain; loose.
Bm1	18 to 38 cm	Dark brown (10YR 4/3 dry); gravelly sand; single grain; loose.
Bm2	38 to 50+ cm	Brown (10YR 4/3 dry); gravelly sand; single grain; loose.

SITE 28

Location: *LSD 3 – Section 28 – Township 33 – Range 2 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating to hummocky; 2-9% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southeast aspect of 3% slope; upper slope position; non-stony*
Vegetation: *Native grasses, wild rose, sage*

Profile Description:

Ah	0 to 10 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; about 10% gravel; single grain; loose.
Bm	10 to 30 cm	Brown (10YR 4/3 dry); sand; about 10% gravel; single grain; loose.
Ck	30 to 40+ cm	Dark yellowish brown (10YR 4/3 dry); sand; about 10% gravel; single grain; loose.

SITE 29

Location: *LSD 14 – Section 34 – Township 33 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial; some eolian in area*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southwest aspect of 3% slope; mid slope position; non-stony; may have been broken a long time ago.*
Vegetation: *Grasses, sage, buckbrush, wolf willow*

Profile Description:

Ah	0 to 20 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; few gravel-sized coarse fragments.
Bm	12 to 50 cm	Brown (10YR 4/3 dry); sand; single grain; loose; few gravel-sized coarse fragments.

SITE 30

Location: *LSD 13 – Section 28 – Township 36 – Range 2 – West 4 Meridian*
Classification:
Subgroup: *Orthic Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *Southeast aspect of 3-4% slope; mid slope position*
Vegetation: *Grasses, sage*

Profile Description:

Ah	0 to 22 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; no coarse fragments.
Bm	25 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; no coarse fragments.

SITE 31

Location: *LSD 13 – Section 35 – Township 36 – Range 3 – West 4 Meridian*
Classification:
Subgroup: *Dark Brown Chernozem*
Series: *Wainwright*
Landform:
Genetic Material: *Glaciofluvial*
Surface Expression: *Undulating; 2-5% slopes*
Drainage/ Perviousness: *Rapidly drained; high perviousness*
Site Features: *East aspect of 3% slope; mid slope position; non-stony*
Vegetation: *Grasses, sage, some buckbrush*

Profile Description:

Ah	0 to 15 cm	Dark grayish brown (10YR 3.5-4/2 dry); sand; single grain; loose; some gravel-sized coarse fragments
Bm	15 to 50+ cm	Brown (10YR 4/3 dry); sand; single grain; loose; some gravel sized-coarse fragments

APPENDIX B

SOIL CHEMICAL DATA

Table B1. pH, Cation Exchange Capacity and Base Saturation Percentage

Site/ Sample	Horizon	pHw	pHc	Base Cations (cmol kg^{-1})	Acid Cations (cmol kg^{-1})	Effective CEC (cmol kg^{-1})	Base Sat_{eff} (%)	CEC_{pH7} (cmol kg^{-1})	Base Sat_{pH7} (%)
PE1-1	Ah	6.1	5.3	5.18	0.02	5.20	99.7	7.35	70.5
PE1-2	Bm	6.6	5.8	4.97	0.00	4.97	100.0	6.21	79.9
PE2-1	LF	6.4	6.1	65.77	0.33	66.10	99.5	66.62	98.7
PE2-2	Ah	5.7	5.1	5.60	0.11	5.71	98.0	8.48	66.0
PE2-3	Bm	5.6	5.0	5.49	0.08	5.57	98.6	7.75	70.8
PE3-1	LF	6.3	5.9	-	-	-	-	-	-
PE3-2	Ah	6.0	5.5	-	-	-	-	-	-
PE3-3	Ae	6.4	5.7	-	-	-	-	-	-
PE3-4	Bm	6.7	6.1	-	-	-	-	-	-
PE4-1	Ah	6.2	5.5	3.29	0.02	3.31	99.5	4.41	74.7
PE4-2	Bm	6.2	5.4	2.23	0.02	2.24	99.2	3.21	69.3
PE5-1	Ah	6.3	5.7	5.15	0.02	5.17	99.7	7.03	73.3
PE5-2	Bm	6.1	5.5	4.27	0.00	4.27	100.0	5.70	75.0
PE6-1	Ah1	7.6	7.4	-	-	-	-	-	-
PE6-2	Ah2	8.4	8.1	-	-	-	-	-	-
PE7-1	Ah	6.1	5.6	7.35	0.02	7.37	99.8	9.55	77.0
PE7-2	Bm	6.3	5.8	6.31	0.00	6.31	100.0	7.58	83.2
PE8-1	Ah1	6.0	5.4	-	-	-	-	-	-
PE8-2	Ah2	6.1	5.5	-	-	-	-	-	-
PE9-1	Ah	6.0	5.5	5.74	0.03	5.77	99.4	8.10	70.9
PE9-2	Bm	5.9	5.3	4.45	0.02	4.46	99.6	6.08	73.1
PE10-1	Ah	5.5	5.0	9.80	0.08	9.87	99.2	16.49	59.4
PE10-2	Bm	5.6	5.3	6.22	0.03	6.25	99.6	9.00	69.2
PE11-1	Ah	5.9	5.4	10.31	0.03	10.34	99.7	14.91	69.1
PE11-2	Bm	6.6	6.1	5.48	0.02	5.50	99.7	6.94	79.0
PE12-1	Ah	6.0	5.4	8.24	0.02	8.25	99.8	10.84	76.0
PE12-2	Bm	6.2	5.5	4.11	0.00	4.11	100.0	5.95	69.1
PE13-1	Ah	5.7	5.2	7.39	0.07	7.46	99.1	10.84	68.2
PE13-2	Bm	6.6	6.2	7.54	0.00	7.54	100.0	9.51	79.3

Table B1. pH, Cation Exchange Capacity and Base Saturation Percentage (continued)

Site/ Sample	Horizon	pHw	pHc	Base Cations (cmol kg^{-1})	Acid Cations (cmol kg^{-1})	Effective CEC (cmol kg^{-1})	Base Sat_{eff} (%)	CEC_{pH7} (cmol kg^{-1})	Base Sat_{pH7} (%)
PE14-1	LF	6.7	6.5	82.09	0.33	82.43	99.6	102.01	80.5
PE14-2	Ahe	5.8	5.3	8.83	0.07	8.90	99.2	11.10	79.6
PE14-3	Ae	6.2	5.5	1.93	0.02	1.94	99.1	2.83	68.1
PE14-4	Bm	6.6	5.9	1.81	0.02	1.83	99.0	2.44	74.1
PE14a-1	LF	6.4	6.3	-	-	-	-	-	-
PE14a-2	Ahe	6.0	5.4	-	-	-	-	-	-
PE14a-3	Ae	6.2	5.5	-	-	-	-	-	-
PE14a-4	Bm	6.4	5.6	-	-	-	-	-	-
PE15-1	Ah	6.3	5.6	5.49	0.02	5.50	99.7	7.54	72.8
PE15-2	Bm	6.5	5.8	4.11	0.02	4.13	99.6	5.48	74.9
PE16-1	Ah	6.2	5.7	-	-	-	-	-	-
PE16-2	Bsa	7.9	7.9	-	-	-	-	-	-
PE16a-1	Ah	5.9	5.2	6.31	0.06	6.38	99.0	10.28	61.4
PE16a-2	Bsa	6.5	5.6	4.70	0.00	4.70	100.0	6.81	69.1
PE16a-3	Bnt	7.5	6.7	8.45	0.00	8.45	100.0	8.65	97.6
PE17-1	Ah	5.7	5.1	10.68	0.14	10.82	98.7	21.59	49.5
PE17-2	Bm	5.8	5.4	13.74	0.04	13.78	99.7	17.48	78.6
PE19-1	Ah	6.3	5.6	7.06	0.02	7.08	99.8	9.64	73.3
PE19-2	Bm	6.6	5.9	5.08	0.00	5.08	100.0	6.81	74.6
PE20-1	Ah	6.2	5.8	-	-	-	-	-	-
PE20-2	Bm	6.9	6.6	-	-	-	-	-	-
PE21-1	Ah	5.6	5.0	5.58	0.06	5.64	98.9	9.98	55.9
PE21-2	Bm	6.0	5.2	4.87	0.03	4.90	99.4	7.24	67.3
PE22-1	Ah	6.3	5.8	14.09	0.05	14.14	99.6	17.99	78.3
PE22-2	Bm	6.0	5.4	5.59	0.03	5.62	99.5	8.18	68.4
PE23-1	Ah	6.7	6.1	7.44	0.02	7.46	99.8	9.34	79.7
PE23-2	Bm	6.9	6.2	5.31	0.00	5.31	100.0	6.47	82.1
PE24-1	Ah	6.1	5.3	3.93	0.04	3.97	99.1	6.17	63.8
PE24-2	Bm	6.6	5.7	3.60	0.02	3.61	99.5	4.84	74.3

Table B1. pH, Cation Exchange Capacity and Base Saturation Percentage (concluded)

Site/ Sample	Horizon	PHw	pHc	Base Cations (cmol kg^{-1})	Acid Cations (cmol kg^{-1})	Effective CEC (cmol kg^{-1})	Base Sat_{eff} (%)	CEC_{pH7} (cmol kg^{-1})	Base Sat_{pH7} (%)
PE25-1	Ah	6.6	5.9	-	-	-	-	-	-
PE25-2	Bm	7.0	6.6	-	-	-	-	-	-
PE26-1	Ah	5.8	5.0	3.22	0.05	3.26	98.6	5.06	63.6
PE26-2	Bm	6.2	5.3	2.28	0.00	2.28	100.0	3.34	68.4
PE26a-1	Ah	6.3	5.5	-	-	-	-	-	-
PE26a-2	Bm	6.5	5.6	-	-	-	-	-	-
PE27-1	Ah	7.2	6.6	-	-	-	-	-	-
PE27-2	Bm	7.3	6.7	-	-	-	-	-	-
PE28-1	Ah	6.8	6.3	12.83	0.02	12.85	99.9	15.55	82.5
PE28-2	Bm	6.9	6.3	8.93	0.00	8.93	100.0	10.41	85.8
PE29-1	Ah	6.1	5.5	6.15	0.02	6.17	99.7	9.25	66.5
PE29-2	Bm	6.8	5.9	4.62	0.02	4.64	99.6	5.65	81.7
PE30-1	Ah	6.7	5.9	4.11	0.02	4.13	99.6	5.27	78.0
PE30-2	Bm	6.7	5.8	3.10	0.00	3.10	100.0	4.03	76.9
PE31-1	Ah	6.7	6.0	-	-	-	-	-	-
PE31-2	Bm1	6.6	5.9	-	-	-	-	-	-
PE31-3	Bm2	6.7	5.8	-	-	-	-	-	-

Appendix Table B2. Exchangeable Cations and Cation Exchange Capacity

Site/ Sample	Horizon	pH	Na	K	Ca	Mg	Al	Fe	Mn	BC	AC	CEC_{pH7}
		($cmol_c\ kg^{-1}$)										
PE01-1	Ah	5.12	0.02	0.35	3.82	1.12	<0.03	<0.01	0.02	5.18	0.02	7.35
PE01-2	Bm	5.43	0.04	0.28	3.67	1.12	<0.03	<0.01	<0.02	4.97	0.00	6.21
PE02-1	LF	6.14	0.05	1.47	55.1	11.2	0.04	0.02	0.26	65.77	0.33	66.62
PE02-2	Ah	4.85	0.03	0.51	3.54	1.67	0.03	<0.01	0.09	5.60	0.11	8.48
PE02-3	Bm	4.99	0.03	0.51	4.05	1.04	0.03	<0.01	0.05	5.49	0.08	7.75
PE04-1	Ah	5.25	0.01	0.23	2.60	0.57	<0.03	<0.01	0.02	3.29	0.02	4.41
PE04-2	Bm	5.12	0.01	0.17	1.73	0.41	<0.03	<0.01	0.02	2.23	0.02	3.21
PE05-1	Ah	5.34	0.01	0.24	4.07	0.96	<0.03	<0.01	0.02	5.15	0.02	7.03
PE05-2	Bm	5.11	0.02	0.13	3.10	1.07	<0.03	<0.01	<0.02	4.27	0.00	5.70
PE07-1	Ah	5.28	0.02	0.59	5.13	1.78	<0.03	<0.01	0.02	7.35	0.02	9.55
PE07-2	Bm	5.41	0.04	0.36	4.15	1.90	<0.03	<0.01	<0.02	6.31	0.00	7.58
PE09-1	Ah	5.22	0.02	0.45	4.18	1.20	<0.03	<0.01	0.03	5.74	0.03	8.10
PE09-2	Bm	4.90	0.04	0.17	3.13	1.18	<0.03	<0.01	0.02	4.45	0.02	6.08
PE10-1	Ah	4.81	0.03	0.95	6.43	2.60	0.03	<0.01	0.05	9.80	0.08	16.49
PE10-2	Bm	4.89	0.64	0.36	2.96	2.88	0.03	<0.01	<0.02	6.22	0.03	9.00
PE11-1	Ah	5.34	0.01	0.67	8.02	1.79	<0.03	<0.01	0.03	10.31	0.03	14.91
PE11-2	Bm	5.55	0.03	0.40	3.99	1.20	<0.03	<0.01	0.02	5.48	0.02	6.94
PE12-1	Ah	5.32	0.03	0.25	6.72	1.37	<0.03	<0.01	0.02	8.24	0.02	10.84
PE12-2	Bm	5.23	0.02	0.23	3.21	0.77	<0.03	<0.01	<0.02	4.11	0.00	5.95
PE13-1	Ah	5.04	0.02	0.75	5.50	1.36	<0.03	<0.01	0.07	7.39	0.07	10.84
PE13-2	Bm	5.68	0.04	0.67	5.31	1.71	<0.03	<0.01	<0.02	7.54	0.00	9.51
PE14-1	LF	6.30	0.05	2.17	73.1	11.5	<0.03	<0.01	0.33	82.09	0.33	102.01
PE14-2	Ahe	5.36	0.01	0.46	7.38	1.22	<0.03	<0.01	0.07	8.83	0.07	11.10
PE14-3	Ae	5.18	0.01	0.19	1.54	0.26	<0.03	<0.01	0.02	1.93	0.02	2.83
PE14-4	Bm	5.19	0.01	0.15	1.43	0.28	<0.03	<0.01	0.02	1.81	0.02	2.44
PE15-1	Ah	5.37	0.01	0.72	3.53	1.36	<0.03	<0.01	0.02	5.49	0.02	7.54
PE15-2	Bm	5.46	0.02	0.52	2.83	0.81	<0.03	<0.01	0.02	4.11	0.02	5.48
PE16a-1	Ah	4.92	0.12	0.36	4.37	1.59	0.03	<0.01	0.04	6.31	0.06	10.28
PE16a-2	Bsa	5.25	0.35	0.25	2.80	1.50	<0.03	<0.01	<0.02	4.70	0.00	6.81
PE16a-3	Bnt	5.89	2.09	0.52	2.10	4.16	<0.03	<0.01	<0.02	8.45	0.00	8.65
PE17-1	Ah	4.75	0.05	1.14	6.96	2.74	0.05	<0.01	0.09	10.68	0.14	21.59
PE17-2	Bm	4.91	0.43	0.61	6.97	5.87	0.03	<0.01	0.02	13.74	0.04	17.48
PE19-1	Ah	5.35	0.02	0.49	5.46	1.20	<0.03	<0.01	0.02	7.06	0.02	9.64
PE19-2	Bm	5.43	0.02	0.25	3.78	1.10	<0.03	<0.01	<0.02	5.08	0.00	6.81

Symbols: BC – sum of exchangeable base cations Ca, Mg, Na and K; AC – sum of exchangeable acid cations Al, Fe and Mn;

CEC_{pH7} – cation exchange capacity determined with 1.0 N ammonium acetate at pH 7.

Appendix Table B2. Exchangeable cations and cation exchange capacity (concluded)

Site/ Sample	Horizon	pH	Na	K	Ca	Mg	Al	Fe	Mn	BC*	AC*	CEC_{pH7}
		($cmol_c\ kg^{-1}$)										
PE21-1	Ah	4.72	0.03	0.43	4.09	1.14	0.03	<0.01	0.04	5.58	0.06	9.98
PE21-2	Bm	4.94	0.07	0.21	3.43	1.23	0.03	<0.01	<0.02	4.87	0.03	7.24
PE22-1	Ah	5.64	0.03	0.98	10.43	3.01	<0.03	<0.01	0.05	14.09	0.05	17.99
PE22-2	Bm	4.97	0.04	0.42	3.76	1.45	0.03	<0.01	<0.02	5.59	0.03	8.18
PE23-1	Ah	5.74	0.02	0.48	5.77	1.31	<0.03	<0.01	0.02	7.44	0.02	9.34
PE23-2	Bm	5.64	0.02	0.20	4.27	0.91	<0.03	<0.01	<0.02	5.31	0.00	6.47
PE24-1	Ah	5.08	0.01	0.50	2.76	0.82	<0.03	<0.01	0.04	3.93	0.04	6.17
PE24-2	Bm	5.43	0.02	0.34	2.53	0.80	<0.03	<0.01	0.02	3.60	0.02	4.84
PE26-1	Ah	4.82	0.01	0.24	2.24	0.81	0.03	<0.01	0.02	3.22	0.05	5.06
PE26-2	Bm	4.99	0.02	0.21	1.53	0.64	<0.03	<0.01	<0.02	2.28	0.00	3.34
PE28-1	Ah	6.01	0.01	0.43	9.99	2.61	<0.03	<0.01	0.02	12.83	0.02	15.55
PE28-2	Bm	5.82	0.02	0.21	6.54	2.27	<0.03	<0.01	<0.02	8.93	0.00	10.41
PE29-1	Ah	5.34	0.01	0.40	4.75	1.09	<0.03	<0.01	0.02	6.15	0.02	9.25
PE29-2	Bm	5.53	0.03	0.20	3.54	0.92	<0.03	<0.01	0.02	4.62	0.02	5.65
PE30-1	Ah	5.54	0.01	0.20	3.07	0.92	<0.03	<0.01	0.02	4.11	0.02	5.27
PE30-2	Bm	5.33	0.01	0.14	2.19	0.81	<0.03	<0.01	<0.02	3.10	0.00	4.03

Appendix Table B3. Electrical Conductivity and Ions in Saturated Paste Extract

Site/ Sample	Horizon	Saturation (%)	pH	E.C. (dS m^{-1})	Al	As	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn
					(mg L^{-1})													
PR1-1	Ah	43.2	6.0	0.16	1.6	< 0.1	0.1	0.1	32.7	< 0.1	< 0.1	< 0.1	< 0.1	0.9	16.4	< 0.1	6.0	0.2
PR1-2	Bm	37.2	6.4	0.18	2.2	< 0.1	0.1	0.2	47.0	< 0.1	< 0.1	< 0.1	< 0.1	0.4	13.1	< 0.1	7.3	0.1
PR2-1	LF	175.0	5.9	0.67	1.1	< 0.1	0.3	0.3	124.1	< 0.1	< 0.1	< 0.1	< 0.1	0.7	66.0	< 0.1	37.2	0.6
PR2-2	AH	42.0	5.8	0.23	1.7	< 0.1	0.1	0.1	32.9	< 0.1	< 0.1	< 0.1	< 0.1	1.4	24.3	< 0.1	11.2	0.8
PR2-3	Bm	38.4	5.8	0.21	2.0	< 0.1	0.1	0.1	41.1	< 0.1	< 0.1	< 0.1	< 0.1	1.5	28.8	< 0.1	6.3	0.4
PR4-1	Ah	36.0	6.2	0.18	1.6	< 0.1	0.1	0.2	38.0	< 0.1	< 0.1	< 0.1	< 0.1	0.4	17.4	< 0.1	5.8	0.3
PR4-2	Bm	31.2	6.4	0.14	2.7	< 0.1	0.2	0.2	33.6	< 0.1	< 0.1	< 0.1	< 0.1	0.6	12.0	< 0.1	4.3	0.1
PR5-1	Ah	34.8	6.5	0.18	4.0	< 0.1	0.1	0.2	49.9	< 0.1	< 0.1	< 0.1	< 0.1	1.9	9.7	< 0.1	6.5	0.2
PR5-2	Bm	31.2	6.5	0.14	1.1	< 0.1	0.1	0.2	16.8	< 0.1	< 0.1	< 0.1	< 0.1	0.2	4.0	< 0.1	4.9	< 0.1
PR7-1	Ah	42.0	6.2	0.23	2.1	< 0.1	0.2	0.2	44.9	< 0.1	< 0.1	< 0.1	< 0.1	0.9	28.9	< 0.1	10.1	0.1
PR7-2	Bm	36.0	6.3	0.22	1.1	< 0.1	0.1	0.1	39.1	< 0.1	< 0.1	< 0.1	< 0.1	0.7	14.2	0.1	10.5	< 0.1
PR9-1	Ah	39.6	6.1	0.19	1.6	< 0.1	0.1	0.2	28.5	< 0.1	< 0.1	< 0.1	< 0.1	0.6	20.7	< 0.1	6.8	0.3
PR9-2	Bm	33.6	6.1	0.14	2.7	< 0.1	0.1	0.1	19.9	< 0.1	< 0.1	< 0.1	< 0.1	1.2	5.9	< 0.1	6.1	0.1
PR10-1	Ah	50.8	5.8	0.24	4.3	< 0.1	0.1	0.2	38.1	< 0.1	< 0.1	< 0.1	< 0.1	2.1	33.4	< 0.1	11.7	0.3
PR10-2	Bm	34.8	5.8	1.25	1.1	< 0.1	0.1	0.1	75.4	< 0.1	< 0.1	< 0.1	< 0.1	0.4	22.4	0.1	55.8	0.1
PR11-1	Ah	44.0	6.2	0.25	3.5	< 0.1	0.1	0.3	45.8	< 0.1	< 0.1	< 0.1	< 0.1	1.9	27.6	< 0.1	10.9	0.4
PR11-2	Bm	28.8	6.6	0.25	1.6	< 0.1	0.2	0.2	57.9	< 0.1	< 0.1	< 0.1	< 0.1	0.7	21.4	< 0.1	10.8	0.1
PR12-1	Ah	40.0	6.3	0.18	4.4	< 0.1	0.1	0.2	40.0	< 0.1	< 0.1	< 0.1	< 0.1	2.2	7.8	< 0.1	7.3	0.2
PR12-2	Bm	31.2	6.4	0.17	1.2	< 0.1	0.1	0.1	50.8	< 0.1	< 0.1	< 0.1	< 0.1	0.4	9.2	< 0.1	5.8	0.1
PR13-1	Ah	44.0	6.0	0.29	11.0	< 0.1	0.2	0.4	60.5	< 0.1	< 0.1	< 0.1	< 0.1	6.3	38.4	< 0.1	13.1	0.8
PR13-2	Bm	38.0	6.7	0.29	3.7	< 0.1	0.1	0.2	59.1	< 0.1	< 0.1	< 0.1	< 0.1	2.9	30.8	< 0.1	12.0	0.1
PR14-1	LF	383.3	6.4	0.76	0.8	< 0.1	0.2	0.3	144.4	< 0.1	< 0.1	< 0.1	< 0.1	0.5	89.4	< 0.1	32.0	1.0
PR14-2	Ahe	51.2	6.0	0.31	2.2	< 0.1	0.1	0.2	42.8	< 0.1	< 0.1	< 0.1	< 0.1	1.8	48.4	< 0.1	10.4	0.4
PR14-3	Ae	32.0	6.4	0.15	1.6	< 0.1	0.1	0.1	21.0	< 0.1	< 0.1	< 0.1	< 0.1	1.2	17.3	< 0.1	3.1	0.2
PR14-4	Bm	30.0	6.9	0.14	2.4	< 0.1	< 0.1	0.1	20.8	< 0.1	< 0.1	< 0.1	< 0.1	1.4	14.4	< 0.1	3.2	0.1

Appendix Table B3. Electrical Conductivity and Ions in Saturated Paste Extract (Continued)

Site/ Sample	Horizon	Saturation (%)	pH	E.C. (dS m^{-1})	Al	As	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn
					(mg L^{-1})													
PR15-1	Ah	40.4	6.4	0.18	1.6	< 0.1	0.1	0.1	31.4	< 0.1	< 0.1	< 0.1	< 0.1	0.6	36.7	< 0.1	6.4	0.2
PR15-2	Bm	32.4	6.6	0.16	1.8	< 0.1	0.1	0.1	17.1	< 0.1	< 0.1	< 0.1	< 0.1	0.5	27.0	< 0.1	4.5	0.1
PR16a-1	Ah	48.0	6.2	0.18	4.6	< 0.1	0.1	0.1	19.9	< 0.1	< 0.1	< 0.1	< 0.1	2.8	7.3	0.1	6.9	0.2
PR16a-2	Bsa	38.0	6.2	0.25	2.8	< 0.1	0.1	0.1	37.6	< 0.1	< 0.1	< 0.1	< 0.1	0.7	5.6	0.1	6.2	0.1
PR16a-3	Bnt	31.2	7.5	0.81	1.2	< 0.1	0.2	0.1	30.7	< 0.1	< 0.1	< 0.1	0.1	1.7	8.5	0.2	14.6	0.1
PR17-1	Ah	60.0	6.1	0.17	5.5	< 0.1	0.1	0.2	39.3	< 0.1	< 0.1	< 0.1	< 0.1	2.9	17.1	< 0.1	8.3	0.3
PR17-2	Bm	46.0	6.5	0.17	1.3	< 0.1	0.1	0.1	20.2	< 0.1	< 0.1	< 0.1	< 0.1	0.8	5.4	< 0.1	6.5	< 0.1
PR19-1	Ah	42.8	6.4	0.16	2.8	< 0.1	0.1	0.2	25.4	< 0.1	< 0.1	< 0.1	< 0.1	1.3	14.8	< 0.1	5.8	0.1
PR19-2	Bm	30.8	6.9	0.15	1.1	< 0.1	0.1	0.1	21.0	< 0.1	< 0.1	< 0.1	< 0.1	0.9	6.7	< 0.1	5.7	< 0.1
PR21-1	Ah	42.8	6.3	0.15	4.9	< 0.1	0.1	0.1	31.6	< 0.1	< 0.1	< 0.1	< 0.1	3.0	10.8	< 0.1	5.7	0.2
PR21-2	Bm	34.0	6.6	0.13	2.2	< 0.1	0.1	0.1	23.6	< 0.1	< 0.1	< 0.1	< 0.1	1.3	4.5	< 0.1	4.6	< 0.1
PR22-1	Ah	72.0	6.6	0.29	3.9	< 0.1	0.1	0.3	56.1	< 0.1	< 0.1	< 0.1	< 0.1	2.3	36.0	< 0.1	13.8	0.2
PR22-2	Bm	39.6	6.2	0.12	1.6	< 0.1	0.1	0.2	15.8	< 0.1	< 0.1	< 0.1	< 0.1	0.4	9.6	< 0.1	4.9	< 0.1
PR23-1	Ah	41.2	7.2	0.18	2.8	< 0.1	< 0.1	0.2	45.8	< 0.1	< 0.1	< 0.1	< 0.1	1.6	18.6	< 0.1	6.0	0.1
PR23-2	Bm	34.2	7.1	0.14	1.3	< 0.1	0.1	0.2	34.4	< 0.1	< 0.1	< 0.1	< 0.1	0.3	5.3	< 0.1	4.3	< 0.1
PR24-1	Ah	38.8	6.4	0.17	2.0	< 0.1	0.1	0.1	44.3	< 0.1	< 0.1	< 0.1	< 0.1	1.0	33.9	< 0.1	4.9	0.3
PR24-2	Bm	32.0	6.7	0.15	2.2	< 0.1	0.1	0.1	35.4	< 0.1	< 0.1	< 0.1	0.1	1.2	19.5	< 0.1	6.4	0.1
PR26-1	Ah	39.6	6.1	0.13	2.8	< 0.1	0.1	0.1	17.9	< 0.1	< 0.1	< 0.1	< 0.1	1.3	13.6	< 0.1	5.9	0.2
PR26-2	Bm	30.8	6.7	0.12	2.9	< 0.1	0.1	0.2	49.3	< 0.1	< 0.1	< 0.1	< 0.1	1.6	10.8	< 0.1	5.2	0.1
PR28-1	Ah	55.6	6.4	0.27	1.1	< 0.1	< 0.1	0.2	41.5	< 0.1	< 0.1	< 0.1	< 0.1	0.7	11.1	< 0.1	12.6	0.2
PR28-2	Bm	38.0	7.1	0.20	0.9	< 0.1	< 0.1	0.1	29.9	< 0.1	< 0.1	< 0.1	< 0.1	1.2	5.1	< 0.1	8.7	< 0.1
PR29-1	Ah	41.2	6.5	0.18	3.8	< 0.1	0.1	0.2	24.2	< 0.1	< 0.1	< 0.1	< 0.1	2.5	15.2	< 0.1	6.2	0.2
PR29-2	Bm	32.0	6.8	0.14	2.3	< 0.1	< 0.1	0.2	23.8	< 0.1	< 0.1	< 0.1	< 0.1	1.1	5.8	< 0.1	5.0	0.2
PR30-1	Ah	35.2	6.8	0.17	3.6	< 0.1	< 0.1	0.2	24.6	< 0.1	< 0.1	< 0.1	< 0.1	1.8	8.7	< 0.1	7.4	0.1
PR30-2	Bm	30.4	7.0	0.12	3.3	< 0.1	0.1	0.2	17.2	< 0.1	< 0.1	< 0.1	< 0.1	0.7	5.5	< 0.1	4.7	< 0.1

Appendix Table B3. Electrical Conductivity and Ions in Saturated Paste Extract (Continued)

Site/ Sample	Horizon	Mo	Na	Ni	P	Pb	S	Se	Si	Sr	Ti	V	Zn	SO_4	BC:Al (molar)
		(mg L^{-1})													
PR1-1	Ah	< 0.1	8.0	< 0.1	1.4	< 0.1	8.0	< 0.1	16.2	0.1	< 0.1	< 0.1	0.9	24.0	14.3
PR1-2	Bm	< 0.1	12.4	< 0.1	1.1	< 0.1	6.8	< 0.1	13.7	0.1	< 0.1	< 0.1	2.3	20.4	13.4
PR2-1	LF	< 0.1	7.5	< 0.1	26.2	< 0.1	16.3	< 0.1	19.3	0.6	< 0.1	< 0.1	0.3	48.9	89.6
PR2-2	AH	< 0.1	11.7	< 0.1	1.3	< 0.1	10.7	< 0.1	16.8	0.1	< 0.1	< 0.1	0.9	32.1	16.9
PR2-3	Bm	< 0.1	13.1	< 0.1	1.5	< 0.1	10.2	< 0.1	18.1	0.1	< 0.1	< 0.1	1.3	30.6	14.9
PR4-1	Ah	< 0.1	8.0	< 0.1	1.7	< 0.1	7.1	< 0.1	12.5	0.1	< 0.1	< 0.1	1.4	21.3	15.9
PR4-2	Bm	< 0.1	12.4	< 0.1	0.9	< 0.1	6.6	< 0.1	13.6	0.1	< 0.1	< 0.1	1.1	19.8	7.8
PR5-1	Ah	< 0.1	10.8	< 0.1	1.0	< 0.1	9.5	< 0.1	21.4	0.1	0.1	< 0.1	2.9	28.5	7.4
PR5-2	Bm	< 0.1	11.7	< 0.1	0.7	< 0.1	7.4	< 0.1	12.8	0.1	< 0.1	< 0.1	0.2	22.2	11.0
PR7-1	Ah	< 0.1	8.8	< 0.1	1.8	< 0.1	11.8	< 0.1	20.1	0.2	< 0.1	< 0.1	1.4	35.4	16.3
PR7-2	Bm	< 0.1	12.6	< 0.1	1.3	< 0.1	13.4	< 0.1	17.0	0.2	< 0.1	< 0.1	1.4	40.2	26.0
PR9-1	Ah	< 0.1	10.0	< 0.1	1.2	< 0.1	9.7	< 0.1	16.2	0.1	< 0.1	< 0.1	0.8	29.1	14.1
PR9-2	Bm	< 0.1	12.1	< 0.1	0.9	< 0.1	7.3	< 0.1	18.7	0.1	< 0.1	< 0.1	< 0.1	21.9	5.5
PR10-1	Ah	< 0.1	8.3	< 0.1	1.9	< 0.1	20.1	< 0.1	23.6	0.2	0.1	< 0.1	1.3	60.3	7.8
PR10-2	Bm	< 0.1	196.2	< 0.1	1.2	< 0.1	217.9	< 0.1	13.6	0.4	< 0.1	< 0.1	1.6	653.7	73.1
PR11-1	Ah	< 0.1	7.6	< 0.1	2.3	< 0.1	14.6	< 0.1	24.7	0.2	0.1	< 0.1	0.5	43.8	10.0
PR11-2	Bm	< 0.1	15.0	< 0.1	1.2	< 0.1	12.4	< 0.1	14.2	0.2	< 0.1	< 0.1	2.0	37.2	24.3
PR12-1	Ah	< 0.1	10.7	< 0.1	1.8	< 0.1	12.1	< 0.1	22.4	0.2	0.1	< 0.1	1.4	36.3	5.7
PR12-2	Bm	< 0.1	12.1	< 0.1	1.0	< 0.1	9.1	< 0.1	12.7	0.1	< 0.1	< 0.1	2.4	27.3	24.4
PR13-1	Ah	< 0.1	10.1	< 0.1	3.3	< 0.1	21.0	< 0.1	41.0	0.2	0.2	< 0.1	2.0	63.0	4.2
PR13-2	Bm	< 0.1	13.0	< 0.1	1.4	< 0.1	13.6	< 0.1	17.9	0.2	0.1	< 0.1	1.7	40.8	11.5
PR14-1	LF	< 0.1	5.8	< 0.1	29.1	< 0.1	19.7	< 0.1	12.3	0.7	< 0.1	< 0.1	1.9	59.1	136.5
PR14-2	Ahe	< 0.1	7.0	< 0.1	4.7	< 0.1	9.8	< 0.1	11.9	0.2	< 0.1	< 0.1	0.3	29.4	17.3
PR14-3	Ae	< 0.1	9.5	< 0.1	0.8	< 0.1	5.0	< 0.1	8.2	0.1	< 0.1	< 0.1	0.3	15.0	9.8
PR14-4	Bm	< 0.1	9.7	< 0.1	0.8	< 0.1	5.4	< 0.1	11.1	0.1	< 0.1	< 0.1	< 0.1	16.2	6.3
PR15-1	Ah	< 0.1	6.8	< 0.1	1.2	< 0.1	6.4	< 0.1	15.6	0.1	< 0.1	< 0.1	1.4	19.2	17.1
PR15-2	Bm	< 0.1	8.6	< 0.1	0.8	< 0.1	5.6	< 0.1	14.3	0.1	< 0.1	< 0.1	0.2	16.8	9.6

Appendix Table B3. Electrical Conductivity and Ions in Saturated Paste Extract (Concluded)

Site/ Sample	Horizon	Mo	Na	Ni	P	Pb	S	Se	Si	Sr	Ti	V	Zn	SO_4	BC:Al (molar)
		(mg L^{-1})													
PR16a-1	Ah	< 0.1	21.2	< 0.1	1.5	< 0.1	13.2	< 0.1	19.7	0.1	0.1	< 0.1	0.2	39.6	3.4
PR16a-2	Bsa	< 0.1	55.8	< 0.1	1.1	< 0.1	18.5	< 0.1	8.6	0.1	< 0.1	< 0.1	2.5	55.5	8.1
PR16a-3	Bnt	< 0.1	247.6	0.3	1.7	0.1	87.3	< 0.1	4.7	0.2	< 0.1	< 0.1	1.1	261.9	22.1
PR17-1	Ah	< 0.1	8.0	< 0.1	1.4	< 0.1	11.6	< 0.1	27.1	0.1	0.1	< 0.1	1.9	34.8	5.0
PR17-2	Bm	< 0.1	31.1	< 0.1	1.3	< 0.1	10.6	< 0.1	21.0	0.1	< 0.1	< 0.1	1.0	31.8	11.6
PR19-1	Ah	< 0.1	6.6	< 0.1	1.2	< 0.1	7.8	< 0.1	15.5	0.1	< 0.1	< 0.1	0.3	23.4	6.8
PR19-2	Bm	< 0.1	7.8	< 0.1	0.8	< 0.1	7.4	< 0.1	9.8	0.1	< 0.1	< 0.1	0.1	22.2	13.8
PR21-1	Ah	< 0.1	8.3	< 0.1	1.3	< 0.1	10.0	< 0.1	26.1	0.1	0.1	< 0.1	1.3	30.0	4.3
PR21-2	Bm	< 0.1	14.1	< 0.1	0.9	< 0.1	8.2	< 0.1	15.1	0.1	< 0.1	< 0.1	1.4	24.6	6.8
PR22-1	Ah	< 0.1	5.7	< 0.1	2.6	< 0.1	11.9	< 0.1	26.8	0.2	0.1	< 0.1	2.4	35.7	11.2
PR22-2	Bm	< 0.1	8.7	< 0.1	0.7	< 0.1	6.2	< 0.1	12.4	0.1	< 0.1	< 0.1	< 0.1	18.6	8.1
PR23-1	Ah	< 0.1	6.5	< 0.1	1.0	< 0.1	6.1	< 0.1	18.7	0.1	< 0.1	< 0.1	2.2	18.3	10.5
PR23-2	Bm	< 0.1	8.8	< 0.1	0.7	< 0.1	4.7	< 0.1	12.7	0.1	< 0.1	< 0.1	1.3	14.1	15.3
PR24-1	Ah	< 0.1	7.5	< 0.1	1.2	< 0.1	6.3	< 0.1	14.5	0.1	< 0.1	< 0.1	2.9	18.9	15.7
PR24-2	Bm	< 0.1	9.2	< 0.1	0.9	< 0.1	5.6	< 0.1	13.8	0.1	< 0.1	< 0.1	1.5	16.8	11.4
PR26-1	Ah	< 0.1	7.8	< 0.1	0.9	< 0.1	5.7	< 0.1	9.4	0.1	< 0.1	< 0.1	0.2	17.1	5.6
PR26-2	Bm	< 0.1	11.8	< 0.1	0.6	< 0.1	4.9	< 0.1	9.8	0.1	< 0.1	< 0.1	2.5	14.7	9.8
PR28-1	Ah	< 0.1	7.1	< 0.1	1.8	< 0.1	10.1	< 0.1	16.3	0.2	< 0.1	< 0.1	0.3	30.3	27.8
PR28-2	Bm	< 0.1	8.4	< 0.1	0.8	< 0.1	7.2	< 0.1	9.4	0.1	< 0.1	< 0.1	0.4	21.6	23.4
PR29-1	Ah	< 0.1	8.6	< 0.1	1.3	< 0.1	8.4	< 0.1	24.0	0.1	< 0.1	< 0.1	0.7	25.2	5.0
PR29-2	Bm	< 0.1	11.8	< 0.1	0.7	< 0.1	5.5	< 0.1	14.6	0.1	< 0.1	< 0.1	0.4	16.5	6.8
PR30-1	Ah	< 0.1	9.4	< 0.1	1.0	< 0.1	7.0	< 0.1	14.9	0.1	< 0.1	< 0.1	0.6	21.0	5.2
PR30-2	Bm	< 0.1	9.9	< 0.1	0.6	< 0.1	4.9	< 0.1	10.2	0.1	< 0.1	< 0.1	0.8	14.7	3.8

Appendix Table B4. Carbon, Nitrogen and Sulphur

Site/Sample	Horizon	Carbon (%)	Nitrogen (%)	Sulfur (%)	C:N	Organic Matter (%)
PR1-1	Ah	0.965	0.089	0.015	10.9	1.7
PR1-2	Bm	0.501	0.048	0.010	10.4	0.9
PR2-1	LF	17.13	1.010	0.126	17.0	29.5
PR2-2	AH	0.991	0.076	0.011	13.1	1.7
PR2-3	Bm	0.765	0.064	0.010	12.0	1.3
PR4-1	Ah	0.652	0.059	0.011	11.1	1.1
PR4-2	Bm	0.281	0.028	0.007	9.9	0.5
PR5-1	Ah	0.836	0.075	0.0142	11.2	1.4
PR5-2	Bm	0.347	0.034	0.0088	10.2	0.6
PR7-1	Ah	1.234	0.109	0.018	11.3	2.1
PR7-2	Bm	0.523	0.054	0.011	9.8	0.9
PR9-1	Ah	0.979	0.089	0.016	11.0	1.7
PR9-2	Bm	0.313	0.033	0.0081	9.6	0.5
PR10-1	Ah	2.534	0.204	0.033	12.4	4.4
PR10-2	Bm	0.676	0.065	0.022	10.5	1.2
PR11-1	Ah	2.296	0.193	0.030	11.9	4.0
PR11-2	Bm	0.694	0.063	0.012	11.0	1.2
PR12-1	Ah	1.745	0.138	0.024	12.6	3.0
PR12-2	Bm	0.610	0.055	0.011	11.0	1.1
PR13-1	Ah	1.612	0.138	0.025	11.7	2.8
PR13-2	Bm	0.767	0.077	0.016	10.0	1.3
PR14-1	LF	26.31	1.375	0.164	19.1	45.4
PR14-2	Ahe	2.427	0.149	0.019	16.3	4.2
PR14-3	Ae	0.176	0.014	0.004	12.9	0.3
PR14-4	Bm	0.077	0.009	0.003	8.2	0.1
PR15-1	Ah	1.066	0.090	0.015	11.8	1.8
PR15-2	Bm	0.559	0.048	0.009	11.6	1.0
PR16a-1	Ah	1.738	0.139	0.025	12.5	3.0
PR16a-2	Bsa	0.655	0.062	0.015	10.5	1.1
PR16a-3	Bnt	0.376	0.042	0.014	8.9	0.6
PR17-1	Ah	3.645	0.266	0.041	13.7	6.3
PR17-2	Bm	1.244	0.113	0.021	11.0	2.1
PR19-1	Ah	1.329	0.112	0.019	11.9	2.3
PR19-2	Bm	0.492	0.045	0.010	11.0	0.8
PR21-1	Ah	1.475	0.117	0.020	12.6	2.5
PR21-2	Bm	0.566	0.052	0.013	10.8	1.0
PR22-1	Ah	3.820	0.281	0.039	13.6	6.6
PR22-2	Bm	0.607	0.058	0.013	10.4	1.0
PR23-1	Ah	1.147	0.096	0.016	12.0	2.0

Site/Sample	Horizon	Carbon (%)	Nitrogen (%)	Sulfur (%)	C:N	Organic Matter (%)
PR23-2	**Bm**	0.545	0.050	0.011	10.8	0.9
PR24-1	**Ah**	0.993	0.085	0.014	11.7	1.7
PR24-2	**Bm**	0.485	0.045	0.008	10.8	0.8
PR26-1	**Ah**	0.823	0.064	0.012	12.8	1.4
PR26-2	**Bm**	0.201	0.018	0.005	11.4	0.3
PR28-1	**Ah**	2.485	0.217	0.039	11.5	4.3
PR28-2	**Bm**	0.715	0.063	0.014	11.3	1.2
PR29-1	**Ah**	1.484	0.115	0.019	12.9	2.6
PR29-2	**Bm**	0.557	0.050	0.010	11.2	1.0
PR30-1	**Ah**	0.775	0.065	0.012	12.0	1.3
PR30-2	**Bm**	0.290	0.029	0.006	10.2	0.5

APPENDIX C

ECOZONE AND ECOREGION DESCRIPTIONS (FROM ECOLOGICAL STRATIFICATION WORKING GROUP 1995)

PRAIRIES ECOZONE

The Prairies ecozone has its base on the Canada – United States border and arcs from the western edge of Alberta to the eastern edge of Manitoba. This zone comprises the northern extension of open grasslands in the Great Plains of North America. Although characterized by relatively little topographic relief with its grasslands and limited forests, and its subhumid to semiarid climate, it is also the most human-altered region in Canada.

Climate The climate of the Prairies ecozone is determined by its location in the heart of North America. The Rocky Mountains to the west impede easy access of moisture-bearing winds from the Pacific. The result is a continental climate, subhumid to semiarid with short hot summers, long cold winters, low levels of precipitation, and high evaporation. Mean annual temperatures range from 1.5°C to 3.5°C. Mean winter temperatures range from -12.5°C to -8°C and mean summer temperatures from 14°C to 16°C. Mean annual precipitation has extreme variability, ranging from 250 mm in the arid grassland regions in southwest Saskatchewan and southeast Alberta, to slightly less than 700 mm in the Manitoba Plain, the warmest and most humid region in the ecozone. A water deficit situation is a characteristic of this ecozone. The presence of high winds accelerates the evaporation of water.

Vegetation The Aspen Parkland constitutes the northern edge of this ecozone, a transition zone to the boreal forest. It is associated with groves of trembling aspen, balsam poplar, intermittent grasslands, and Black Chernozemic soils. The Aspen Parkland has expanded southward considerably since the prairie fires were effectively stopped by settlement. Natural grassland vegetation was dominated by spear, wheat, and blue grama grass. Sagebrush is abundant. Yellow cactus and prickly pear are found on drier sites. Its shortgrass prairie section occupies the driest southerly arc of this ecozone, where Brown Chernozemic soils are dominant. The moist mixed grasslands are associated with the Dark Brown Chernozemic soils to the north.

Landforms and Soils The ecozone is underlain for the most part by Cretaceous shales and by flat-lying Paleozoic limestone in southeastern Manitoba. The surface of this nearly level to rolling plain consists largely of hummocky glacial moraine and level to gently undulating lacustrine deposits. The relatively high natural fertility and good moisture-holding capacity of the area's Chernozemic soils make them highly productive for agriculture. The most productive soils are found on the Black, Dark Gray and Dark Brown Chernozems of the Aspen Parkland and the tall and moist mixed grass prairie. Relatively flat topography is particularly conducive to highly mechanized farming. Depending on rainfall, there are millions of small depressional wetland areas in the form of sloughs, ponds and marshes. The greatest concentration occurs in the subhumid northern grasslands and adjacent Aspen Parkland. Most of the major rivers originate in the Rocky Mountains and flow in an easterly direction across the ecozone. They are dominated by rainfall as well as snowmelt and glacial runoff at their headwaters. Many of the smaller rivers and streams have pronounced variability in streamflow and are often dry for extended periods.

Wildlife Characteristic mammals include mule deer, elk (wapiti), coyote, pronghorn antelope, badger, white-tailed jack rabbit, Richardson's ground squirrel, and northern pocket gopher. White-tailed deer are a recent invader. Bird species include ferruginous hawk, Swainson's hawk, American avocet, and burrowing owl. Great blue heron, black-billed magpie, northern oriole, veery, and brown thrasher are other representative birds. The wetlands in the Prairies ecozone provide major breeding, staging, and nesting habitat for migratory waterfowl using the North American Flyway.

These wetlands provide critical habitat for more than half of North America's waterfowl. The transformation of the Prairies ecozone by agricultural activities has resulted in dramatic reduction in habitat for many species. It has resulted in a significant number of extirpated, threatened and endangered wildlife species relative to its area and population.

Human Activities Agriculture is the dominant land use in the prairie landscape. Called the breadbasket of Canada, over 60% of Canada's cropland and 80% of its rangeland, and pasture are located in the ecozone. The other major activities contributing to the economy are mining (coal, potash, mineral, and aggregates) and oil and gas production. Despite the dominance of agricultural activities on the landscape, approximately 80% of the population of 3.8 million are found in urban communities. The major population centres are Calgary, Edmonton, Winnipeg, Regina, and Saskatoon.

ASPEN PARKLAND

This ecoregion extends in a broad arc from southwestern Manitoba, northwestward through Saskatchewan to its northern apex in central Alberta. The parkland is considered transitional between the boreal forest to the north and the grasslands to the south. The climate is marked by short, warm summers and long, cold winters with continuous snow cover. The mean annual temperature is approximately 1.5°C. The mean summer temperature is 15°C and the mean winter temperature is -12.5°C. The mean annual precipitation ranges 400–500 mm. The ecoregion is classified as having a transitional grassland ecoclimate. Most of the ecoregion is now farmland but in its native state, the landscape was characterized by trembling aspen, oak groves, mixed tall shrubs, and intermittent fescue grasslands. Open stands of trembling aspen and shrubs occur on most sites, and bur oak and grassland communities occupy increasingly drier sites on loamy Black Chernozemic soils. Poorly drained, Gleysolic soils support willow and sedge species. This broad plains region, underlain by Cretaceous shale, is covered by undulating to kettled, calcareous, glacial till with significant areas of level lacustrine and hummocky to ridged fluvioglacial deposits. Associated with the rougher hummocky glacial till, landscapes are numerous tree-ringed, small lakes, ponds, and sloughs that provide a major habitat for waterfowl. The ecoregion also provides a major breeding habitat for waterfowl and includes habitat for white-tailed deer, coyote, snowshoe hare, cottontail, red fox, northern pocket gopher, Franklin's ground squirrel, and bird species like sharp-tailed grouse and black-billed magpie. Owing to its favourable climate and fertile, warm black soils, this ecoregion represents some of the most productive agricultural land in the Prairies. It produces a wide diversity of crops, including spring wheat and other cereals, oilseeds, as well as forages and several specialty crops. Dryland continuous cropping methods for spring wheat and other cereal grains are prevalent. Major communities include Red Deer, Edmonton, Lloydminster, North Battleford, Humboldt, Yorkton, and Brandon. The population of the ecoregion is approximately 1 689 000.

MOIST MIXED GRASSLAND

This ecoregion comprises the northern extension of open grasslands in the Interior Plains of Canada and is closely correlated with semiarid moisture conditions and Dark Brown Chernozemic soils. The mean annual temperature is approximately 2.5°C. In some areas of southwestern Alberta the mean annual temperature can reach 5°C. The mean summer temperature is 15.5°C and the mean winter temperature is -11°C. The mean annual precipitation ranges 350–400 mm. Native

vegetation is relegated to nonarable pasturelands, dominated by spear grass and wheat grass, and a variety of deciduous shrubs including buckbrush, chokecherry, wolf willow, and saskatoon. Patches of scrubby aspen, willow, cottonwood, and box-elder occur to a limited extent on shaded slopes of valleys, on river terraces, and ringing nonsaline depressional sites covered with meadow grasses and sedges. Local saline soil areas support alkali grass, wild barley, red sampire, and sea blite. The region is composed of upper Cretaceous sediments and covered almost entirely by hummocky to kettled glacial till and level to very gently undulating, sandy to clayey lacustrine deposits. Although Dark Brown Chernozemic soils are dominant, significant areas of Solonetzic soils occur, particularly in eastern Alberta. Intermittent sloughs and ponds provide habitat for waterfowl. White-tailed deer, pronghorn antelope, coyote, rabbit, and ground squirrel are common in the region. Spring wheat and other cereal grains are produced by employing a wheat or other grain-fallow rotation. Oilseed crops are also becoming increasingly important. Minor irrigation of these crops occurs near Lake Diefenbaker in Saskatchewan and in southern Alberta. Waterfowl hunting is common, and recreation is important around several large reservoirs. Major communities include Fort Macleod, Lethbridge, Drumheller, Rosetown, Unity, Biggar, Saskatoon, Moose Jaw, Regina, Estevan, and Weyburn. The total population of the ecoregion is approximately 656 000.

MIXED GRASSLAND

This semiarid grassland ecoregion in southwestern Saskatchewan and southeastern Alberta forms part of the shortgrass prairie in the Great Plains of North America. The mean annual temperature is approximately 3.5°C. In southern Alberta, west of the Cypress Upland ecoregion mean annual temperatures can exceed 5°C. The mean summer temperature is 16°C and the mean winter temperature is -10°C. The mean annual precipitation ranges 250–350 mm. Moisture deficits in late summer are caused by low precipitation and high evapotranspiration. The natural vegetative cover is dominated by spear grass, blue grama grass, and wheat grass. June grass and dryland sedge are significant associates. Blue grama and spear grass predominate on drier sites, along with dwarf sedges. A variety of shrubs and herbs also occurs, but sagebrush is most abundant, and on the driest sites yellow cactus and prickly pear can be found. Scrubby aspen, willow, cottonwood, and box elder occur to a limited extent on shaded slopes of valleys and river terraces. Local saline areas support alkali grass, wild barley, greasewood, red sampire, and sea blite. The region is composed of upper Cretaceous sediments and is covered almost entirely by dissected to kettled, loamy glacial till, undulating to dissected, loamy lacustrine sediments, and hummocky sandy eolian deposits. The region skirts the Cypress Hills with the area to the south being drained by the Missouri River system, and the area to the north by the South Saskatchewan River. The soils are mainly Brown Chernozemic with significant areas of Solonetzic soils. Pronghorn antelope, deer, sage grouse, short-horned lizard, western rattlesnake, coyote, rabbit, and ground squirrel are common species in the region. The production of spring wheat and other cereal grains occurs by employing a grain-fallow rotation. Flaxseed and durum wheat are also grown. About half of the region is cultivated with the remainder being used for pasture or rangeland. As part of the North American waterfowl migratory flyway and with its diverse wildlife habitat, the region provides opportunities for hunting and recreation. The major communities include Medicine Hat, Leader, Swift Current, Assiniboia, Maple Creek, Shaunavon, and Kindersley. The population of the ecoregion is approximately 187 200.

APPENDIX D

CRITICAL LOAD ESTIMATION OF LAND SYSTEMS

Appendix Table D1. Critical Load Estimation of Land Systems

Land System Symbol	Soil Zone	Soil Series	Series (% of LS)[1]	Data Source	Series Sensitivity	Overall LS Sensitivity
01.3d.01 Sounding Valley	Brown	Bingville	40	Site 17	L	L(100)[2]
		Ronalaine	40	AGRASID	L	
		Bullpound	10	AGRASID	L	
		Dishpan	10	AGRASID	L	
01.3d.02 Sedalia Plain	Brown	Hemaruka	40	AGRASID	L	L(100)
		Halliday	40	AGRASID	L	
		Maleb	10	AGRASID	L	
		Cecil	10	AGRASID	L	
01.4d.02 Calendula Upland	Brown	Maleb	40	AGRASID	L	L(100)
		Foremost	40	AGRASID	L	
		Hemaruka	10	AGRASID	L	
		Ronalaine	10	AGRASID	L	
01.4d.18 Salt Lake Upland	Dark Brown	Hughenden	80	AGRASID	L	L(100)
		Neutral	10	AGRASID	L	
		Onnevue	10	AGRASID	L	
01.4f.02 Sibbald Plain	Brown	Chin Acadia	80	AGRASID	L	L(100)
		Valley	10	AGRASID	L	
		Maleb	10	AGRASID	L	
01.4f.03 Mere Plain	Brown	Bingville	40	Sites 17 (i)[3]	L	M(10)L(90)
		Pemukan	40	AGRASID	L	
		Cavendish	10	Site 19	M	
		Chin	10	AGRASID	L	
02.4a.04 Pacific Creek Upland	Dark Brown	Hughenden	90	AGRASID	L	L(100)
		Flagstaff	10	AGRASID	L	
02.4a.05 Grassy Island Plain	Dark Brown	Wainwright	80	Site 15, 16, 16a, 21, 23, 2,	M	M(80)L(20)
		Metisko	10	25, 26, 29	L	
		Gough Lake	10	Site 11(i) AGRASID	L	
02.4a.06 Loverna Plain	Dark Brown	Metisko	45	Site 28	L	M(50)L(50)
		Wainwright	45	Site 22, 27	M	
		Coronation	10	AGRASID	L	
02.4a.08 Altario Upland	Dark Brown	Hughenden	80	AGRASID	L	L(100)
		Kirriemuir	10	AGRASID	L	
		Altario	10	AGRASID	L	
05.2a.01 St. Lawrence Hills	Dark Brown	Hughenden	80	AGRASID	L	L(100)
		Gleysols	10	AGRASID	L	
		Provost	10	AGRASID	L	

[1] LS – Land System

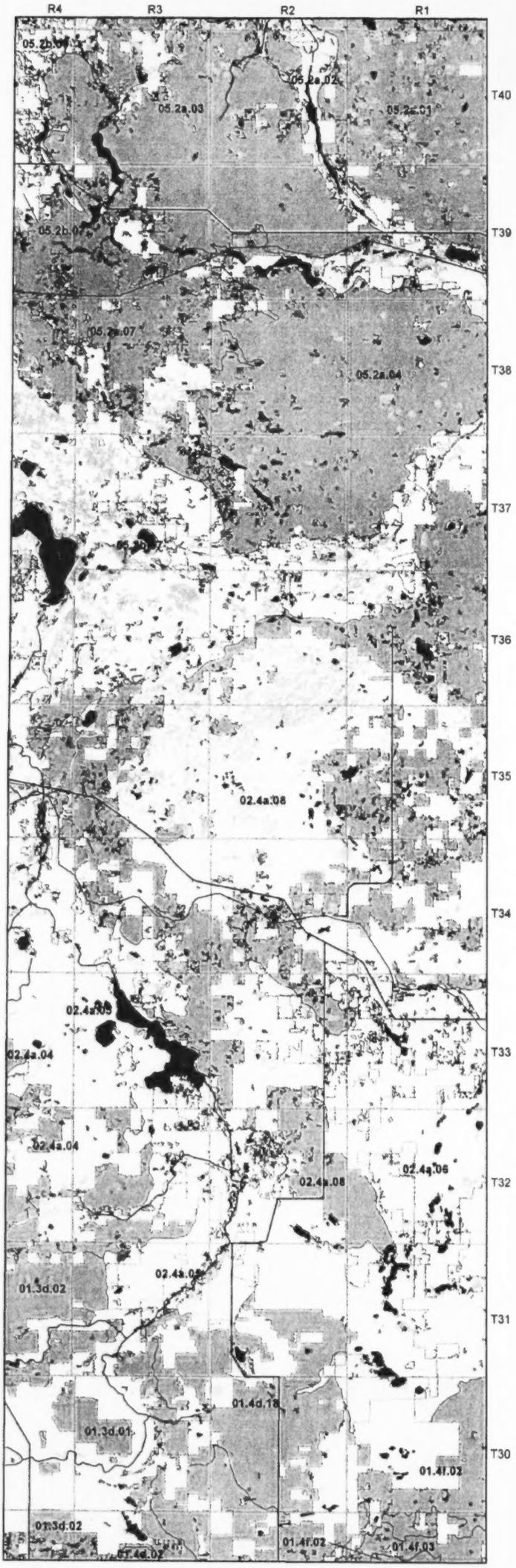
[2] Proportion of Moderate (M) or Low (L) sensitivity soils.

[3] (i) – inferred; information is inferred from the site indicated, which occurs in a different Land System.

Table D1. Critical Load Estimation of Land Systems (Concluded)

Land System	Soil Zone	Soil Series	Series (% of LS)	Data Source	Series Sensitivity	Overall LS Sensitivity
05.2a.02 Gillespie Lowland	Dark Brown	Metisko	30	Site 11	L	M(40)L(60)
		Dolcy	20	AGRASID	L	
		Wainwright	40	Site 12	M	
		Gleysols	10	AGRASID	L	
05.2a.03 Black Creek Upland	Dark Brown	Hughenden	80	AGRASID	L	L(100)
		Provost	10	AGRASID	L	
		Gleysols	10	AGRASID	L	
05.2a.04 Falcon Plain	Dark Brown	Hughenden	40	AGRASID	L	L(100)
		Provost	40	AGRASID	L	
		Coronation	10	AGRASID	L	
		Solonetzic	10	AGRASID	L	
05.2a.07 Hansman Plain	Dark Brown	Coronation	40	AGRASID	L	L(100)
		Provost	40	AGRASID	L	
		Metisko	10	Site 11(i)	L	
		Solonetzic	10	AGRASID	L	
05.2b.07 Sunken Lake Plain	Dark Brown	Wainwright	60	Site 1, 2, 3, 4, 5,	M	M(60)L(40)
		Metisko	20	6, 7, 13, 14, 14a,	L	
		Houcher	10	30, 31	M	
		Dolcy	5	AGRASID	L	
		Gleysols	5	AGRASID	L	
				AGRASID		
05.2b.09 David Lake Plain	Dark Brown	Metisko	40	Site 10	L	M(40)L(60)
		Wainwright	40	Site 8, 9	M	
		Coronation	10	AGRASID	L	
		Monitor	10	AGRASID	L	

Land Systems, Land Cover and Soil Sensitivity to Acid Inputs in the Provost - Esther Grid Cell



LEGEND

LAND SYSTEM SYMBOL	LAND SYSTEM NAME	SOIL ZONE	MAJOR SOIL SERIES	MINOR SOIL SERIES	ACIDIFICATION SENSITIVITY (% of Area)	GENERAL DESCRIPTION
01.3d.01	Sounding Valley	Brown	Bingville (Orthic Brown Chernozem) Rosedale (Solonetzic Brown Chernozem)	Bullpound (Brown Solonetz) Dishpan (Regic Gleysol)	Low - 100%	Landscape is undulating with some blowouts. Brown Chernozems developed on moderately coarse textured glaciofluvial sediments and medium textured till. Minor Solonetz and Gleysols.
01.3d.02	Bodalle Plain	Brown	Hussar (Brown Solodized Solonetz) Halkirk (Brown Solod)	Meloy (Orthic Brown Chernozem) Coal (Solonetzic Brown Chernozem)	Low - 100%	Landscape is undulating with some hummocky. Brown Solonetz developed on predominately fine textured till. Minor Chernozems.
01.4d.05	Columbia Upland	Brown	Meloy (Orthic Brown Chernozem) Fenwood (Orthic Brown Chernozem)	Hortensia (Brown Solodized Solonetz) Ronalane (Solonetzic Brown Chernozem)	Low - 100%	Landscape is hummocky. Brown Chernozems developed on moderately fine textured till. Minor Solonetz.
01.4d.18	Eol Lake Upland	Dark Brown	Hughendan (Orthic Dark Brown Chernozem)	Neutral (Regic Dark Brown Chernozem) Ominvale (Solonetzic Dark Brown Chernozem)	Low - 100%	Landscape is hummocky with some ridged. Dark Brown Chernozems developed on moderately fine textured till. Significant eroded soils.
01.4f.02	Meloett Plain	Brown	Chin (Orthic Brown Chernozem)	Abadis Valley (Calcareous Brown Chernozem) Meloe (Orthic Brown Chernozem)	Low - 100%	Landscape is undulating with some hummocky. Brown Chernozems on medium textured glaciolacustrine sediments. Minor fine textured soils
01.4f.03	Vera Plain	Brown	Bingville (Orthic Brown Chernozem) Pemukan (Orthic Brown Chernozem)	Cavendish (Orthic Brown Chernozem) Chin (Orthic Brown Chernozem)	Medium - 10% Low - 90%	Landscape is undulating. Brown Chernozems developed on moderately coarse and gravelly, very coarse glaciofluvial sediments.
02.4a.04	Pacific Creek Upland	Dark Brown	Hughendan (Orthic Dark Brown Chernozem)	Peagent (Solonetzic Dark Brown Chernozem)	Low - 100%	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till.
02.4a.05	Grassy Island Plain	Dark Brown	Wainwright (Orthic Dark Brown Chernozem)	Meloflat (Orthic Dark Brown Chernozem) Gough Lake (Regic Gleysol)	Medium - 55% Low - 39%	Landscape is undulating with some knoll, closed basin and dunes. Dark Brown Chernozems on very coarse textured fluvioeolian sediments. Minor Gleysols and fine textured soils.
02.4a.06	Laverne Plain	Dark Brown	Meloflat (Orthic Dark Brown Chernozem) Wainwright (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem)	Medium - 98% Low - 90%	Landscape is undulating with some dunes and hummocky. Dark Brown Chernozems developed on coarse textured glaciofluvial and very coarse textured fluvioeolian sediments.
02.4a.08	Alhada Upland	Dark Brown	Hughendan (Orthic Dark Brown Chernozem)	Kinbrae (Orthic Dark Brown Chernozem) Alhada (Regic Dark Brown Chernozem)	Low - 100%	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till. Significant eroded soils.
05.3a.01	St. Lawrence Hills	Dark Brown	Hughendan (Orthic Dark Brown Chernozem)	Gleysols Provost (Orthic Dark Brown Chernozem)	Low - 100%	Landscape is undulating with some hummocky and ridged. Dark Brown Chernozems on moderately fine textured till. Minor Gleysols.
05.3a.03	Gillespie Lowland	Dark Brown	Meloflat (Orthic Dark Brown Chernozem) Daley (Orthic Dark Brown Chernozem)	Wainwright (Orthic Dark Brown Chernozem) Gleysols	Medium - 38% Low - 70%	Landscape is undulating with some wetland depression and numerous water bodies. Dark Brown Chernozems on moderately coarse textured glaciofluvial sediments and coarse textured glaciofluvial materials over moderately fine textured till. Minor Gleysols.
05.3a.05	Black Creek Upland	Dark Brown	Hughendan (Orthic Dark Brown Chernozem)	Provost (Orthic Dark Brown Chernozem) Gleysols	Low - 100%	Landscape is hummocky. Dark Brown Chernozems developed on moderately fine textured till. Minor Gleysols.
05.3a.04	Falcon Plain	Dark Brown	Hughendan (Orthic Dark Brown Chernozem) Provost (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem) Solonetzic soils	Low - 100%	Landscape is a hummocky with some undulating. Dark Brown Chernozems developed on moderately fine textured till and medium textured material over moderately fine textured till. Minor Solonetz.
05.3a.07	Hairstreak Plain	Dark Brown	Coronation (Orthic Dark Brown Chernozem) Provost (Orthic Dark Brown Chernozem)	Meloflat (Orthic Dark Brown Chernozem) Solonetzic soils	Low - 100%	Landscape is undulating with some hummocky. Dark Brown Chernozems developed on medium textured glaciofluvial sediments and medium textured materials over moderately fine textured till. Minor Solonetz and coarse textured soils.
05.3b.07	Sunken Lake Plain	Dark Brown	Wainwright (Orthic Dark Brown Chernozem) Meloflat (Orthic Dark Brown Chernozem) Hoosher (Regic Dark Brown Chernozem)	Daley (Orthic Dark Brown Chernozem) Gleysols	Medium - 60% Low - 40%	Landscape is dunes with some undulating. Dark Brown Chernozems developed on very coarse to coarse textured glaciofluvial and fluvioeolian sediments. Minor Gleysols. Significant eroded soils.
05.3b.08	Devil Lake Plain	Dark Brown	Meloflat (Orthic Dark Brown Chernozem) Wainwright (Orthic Dark Brown Chernozem)	Coronation (Orthic Dark Brown Chernozem) Minotor (Regic Dark Brown Chernozem)	Medium - 40% Low - 60%	Landscape is undulating. Dark Brown Chernozems on moderately coarse textured glaciofluvial sediments. Significant eroded soils.

SYMBOLS

Base Map Features

- Lakes
- Rivers
- Roads
- Railways
- Townships
- Land System Boundary

Land Cover Types

- Grasslands
- Shrubs
- Trees
- Cultivated

Sensitivity to Acidic Inputs

- Low
- Mixture Low / Medium
- Medium

N

5 0 5 10

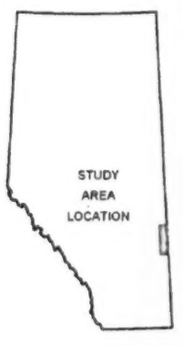
Kilometres

Scale 1 : 150 000

Projection : UTM Zone 12
NAD 83

GIS File : LAND1.APR

March 2000



Soils information from the AGRASID database (CAESA 1988) and land cover information form the Prairie Farm Rehabilitation Administration.

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